Astronomy®
special issue

COLLECTOR'S EDITION

MARS

Explore the Red Planet's past, present, and future

Display until February 14, 2006

Mars rovers: The complete story

36 pages of science, discoveries, and photos

PLUS:

Water found: Is life next?

How we'll send astronauts to Mars

The Red Planet in myth & reality

On the launch pad: The super-roving Mars Science Laboratory

The Opportunity rover explores Endurance Crater, where exposed bedrock proved water once drenched Mars' surface. NASA

$12.95 CANADA

66

7 7562 4 57087 0

Astronomy.com

MARS COLLECTOR'S EDITION - 2006

contents

4 **Red Planet spectacular**

6 **Mars talk**

8 **Fourth rock from the Sun**
The latest spacecraft are showing a Mars more complex and fascinating than ever — and solving some long-standing mysteries. *Robert Burnham*

16 **So where are the Martians?**
Dreams of life on Mars have yet to be fulfilled, but scientists are more optimistic today than they've been in decades. *David Chandler*

24 **Before the Space Age**
In the years before spacecraft probed the martian surface, observers put eyeball to eyepiece and reached some outlandish conclusions. *David S. F. Portree*

32 **Mars Attacks!**
For 150 years, the Red Planet has cast a spell on earthlings. *Jeff Moore*

40 **First visitors from Earth**
Early flybys implied the Red Planet's nickname should be Dead Planet instead, but the first orbiters changed our view of Mars again. *Mark Robinson*

50 **The view from orbit**
Spacecraft provide a global view of martian features, from massive volcanoes to small gullies. *Nadine Barlow*

58 **The great Mars road trip**
Two far-ranging rovers have rewritten martian history. *Robert Burnham*

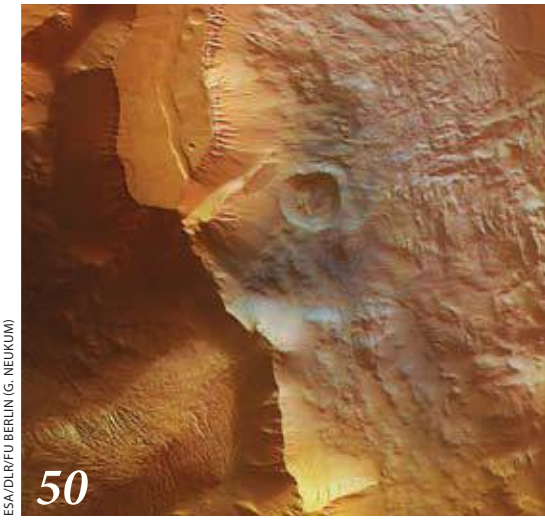
62 **Spirit explores Gusev Crater**
After 6 months, the Spirit rover found signs of a wet past. *Sarah Webb*

78 **Opportunity roves Meridiani Planum**
The Opportunity rover found evidence for water nearly everywhere it looked. *David Chandler*

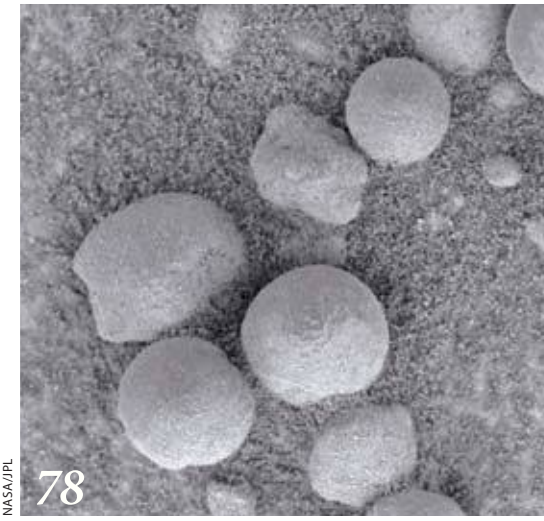
94 **Mars or bust**
Future exploration will include advanced landers, orbiters, and eventually, manned flight. *Frank Sietzen, Jr.*

108 **Mars photo**
The European Space Agency's Mars Express surveys Vallis Marineris.

WARNER BROS./THE KOBAL COLLECTION/INDUSTRIAL LIGHT & MAGIC



ESA/DLR/FU BERLIN (G. NEUKUM)



NASA/JPL

NASA/U.S. GEOLOGICAL SURVEY

Red Planet spectacular

Mars grabbed hold of our collective imagination centuries ago — and has yet to yield its grip. From the time humans first looked to the sky, this bright point of light begged for attention. Its ruddy glow stands out like a sore thumb against the white sparkle most of its heavenly

companions display. And its brightness varies from dazzling to inconspicuous — a far greater range than any other celestial body.

It didn't take long for ancient skywatchers to spot its motion among the stars. Mars and a handful of other such objects were christened "planets" after a Greek word meaning "wanderer." Even before Galileo (1564–1642) turned his first telescope skyward, Danish skywatcher Tycho Brahe (1546–1601) charted Mars' motion in exquisite detail. These meticulous observations helped German astronomer Johannes Kepler (1571–1630) develop his three laws of planetary motion, which ultimately placed the Sun, not Earth, in the solar system's center.

The exploration of Mars really took off in the 17th century, when observers with telescopes turned the Red Planet from a dot in the sky into a real world. First, they saw vague dark markings and gleaming polar caps. Later, astronomers charted multiple features in amazing detail, especially when you consider Mars never ventures closer to Earth than 35 million miles.

As telescopes improved, so did our imaginations. In the latter part of the 19th century, Italian observer Giovanni Schiaparelli discovered *canali* — Italian for "channels" — which was promptly mistranslated into English as "canals." Percival Lowell (1855–1916) took this idea and ran with it. He charted an elaborate network of dark, linear markings, which he believed to be irrigation canals carrying water from the polar caps to a thirsty civilization.

The idea exploded in the public's consciousness. Novelists filled libraries with stories of fictional Martians, while scientists debated the possibility that life, or at least water, exists on Mars. The scientific debate raged until the 1960s, when the first Mariner spacecraft returned images of a desolate, cratered world.

That pretty much closed people's minds to the idea Mars could be any more hospitable than the barren Moon — at least until the 1970s. This was when Mariner 9 and the two Viking missions revealed a world of valleys and volcanoes, dust devils and icy winds, and landforms that look like water-carved channels. Although the prospects for life still looked dismal, scientists poured renewed energy into exploring the Red Planet.

The first years of the 21st century find three spacecraft studying Mars from above and two rovers probing the surface. The debate over water on Mars no longer exists — the rovers proved this liquid gold once drenched the surface. The big question now is *when* did the water flow. As scientists learn more about the keys to life, some think life might have gained a toehold on the watery plains of early Mars.

During the next several years, sophisticated orbiters and surface probes will advance the search. But robots are only our surrogates. Eventually, humans will go to Mars — life seeking life in the rusty deserts of an alien world.

Mars and Martians are a compelling story — one too big to be told in the pages of a single monthly issue. That's why *Astronomy* brought together top Mars scientists and science writers in this special edition. You'll find everything about Mars from early musings to the latest discoveries — and what the future holds in store.

Welcome to the Red Planet.

Richard Talcott
Editor

MARS
COLLECTOR'S EDITION – 2006

Editor Richard Talcott
Art Director Carole Ross

EDITORIAL STAFF
Editoral Director David J. Eicher
Managing Editor Dick McNally
Senior Editor Robert Burnham
Associate Editors Michael E. Bakich, Francis Reddy
Copy Editor Laura Baird
Assistant Editors Liz Kruesi, Matt Quandt
Editorial Associate Jeremy McGovern
Editorial Assistant Valerie Penton

CONTRIBUTING EDITORS
Bob Berman, Glenn F. Chaple, Jr., Stephen J. Edberg, Phil Harrington, David Healy, Ray Jayawardhana, Alister Ling, Steve Nadis, Tom Polakis, Martin Ratcliffe, William Schomaker, John Shibley

ART STAFF
Illustrators Roen Kelly, Theo Cobb
Production Coordinator Joni Hauser

EDITORIAL ADVISORY BOARD
Buzz Aldrin, Marcia Bartusiak, Timothy Ferris, Alex Filippenko, Adam Frank, John S. Gallagher III, William K. Hartmann, Paul Hodge, Anne L. Kinney, Edward Kolb, Stephen P. Maran, S. Alan Stern, James Trefil

[Kalmbach Publishing Co.]
President Gerald B. Boettcher
Vice President, Editorial, Publisher Kevin Keefe
Vice President, Marketing Michael R. Stephens
Vice President, Advertising Scott Stollberg
Corporate Art Director Maureen M. Schimmel
Production Manager Annette Wall
Corporate Circulation Director Michael Barbee
Group Circulation Manager Michelle Spehr
Circulation Coordinators Erin Gallaher, Jaclyn Witthuhn
Single Copy Sales Director Jerry Burstein

ADVERTISING DEPARTMENT
(888) 558-1544
Advertising Services Manager Sara Malin Everts
severts@kalmbach.com
Advertising Sales Manager Howard Hoerl
hhoerl@astronomy.com
Advertising Sales Representative Ken Kozerski
kkozerski@astronomy.com
Ad Services Representative Leah Hamann
lhamann@kalmbach.com

RETAIL TRADE ORDERS AND INQUIRIES
(800) 558-1544, ext. 818; outside the U.S. and Canada: (262) 796-8776, ext. 818

SPECIAL E-MAIL ADDRESSES
Ad Sales adsales@astronomy.com
Books books@astronomy.com
Customer Service customerservice@kalmbach.com
Letters letters@astronomy.com
Products products@astronomy.com
Reader gallery readergallery@astronomy.com

Mars 2006 (ISBN 0–89024–651–3) is published by Kalmbach Publishing Co., 21027 Crossroads Circle, P. O. Box 1612, Waukesha, WI 53187–1612. Astronomy editorial phone: (262) 796-8776; advertising: (888) 558-1544; customer service and sales: (800) 533-6644; fax: (262) 796-1615; e-mail: customerservice@kalmbach.com. SINGLE COPY PRICE: U.S. $9.95, Canada $12.95, and Foreign $12.95. Canadian price includes GST. BN 12271 3209 RT. Canadian and foreign orders payable in U.S. funds. Canadian International Publications Mail Products Agreement no. 40010760. Expedited delivery available for additional $2.50 domestic and Canadian, $6 foreign. POSTMASTER: Send address changes to: Mars 2006, Kalmbach Publishing Co., 21027 Crossroads Circle, Waukesha, WI 53187–1612.

Copyright © 2005 Kalmbach Publishing Co. Title registered as trademark; all rights reserved. Material in this publication may not be reproduced in any form without permission.
Standard class postage paid at Waukesha, WI, and additional offices. Printed in the U.S.A.

Macroscopic Optics at Microscopic Prices™

FREE 144 PG. CATALOG!

Visit our website (**www.SurplusShed.com**) for thousands of optics and electronic bargains for fun, hobby, education, or profit. In addition to our regular inventory of low-cost, quality objective lenses, eyepieces and other astronomy-related items, we have recently purchased the remaining assets of Wollensak Optical, Parker Products, and most of A. Jaegers Optics. We have 3 huge warehouses full of stuff you need.
New items added every week.

To order call: 877-7SURPLUS toll free.
Free 144-page catalog. E-mail us for one at:
sales@surplusshed.com or write:
Surplus Shed, 1050 Maidencreek Rd.,
Fleetwood, PA 19522.

SURPLUSHED℠

www.SurplusShed.com

High Quality ALT-AZ Mounts

DiscMounts manufactures high-quality Alt-Az mounts and tripods for the ultimate grab-and-go portable telescope system. Incredibly smooth and rigid even at high powers. Designed from the start to use DSCs with all internal cables and encoders. Manufactured in the USA from aircraft aluminum and stainless steel. No welds, no paint, completely machined and hard-coat anodized.

To order call: (954) 475-8574 or e-mail **tom@discmounts.com**. Pat. Pending

DiscMounts, Inc
HANDCRAFTED BY TOM PETERS

www.discmounts.com

Green Lasers

Beam of Light Technologies, Inc.
Green Lasers for Star Pointing, Star Finders, and Scope Mounting.

www.z-bolt.com

"Enter Astronomy magazine code **532"** at our online store.
Receive 10% off
ALL ASTRONOMY MODELS!!!
Faxed PO's accepted for universities, corporations, government agencies, and the U.S. Armed Forces.

To order call: **877-801-9299** toll free.
Fax: 603-309-6020

www.z-bolt.com

Binoculars & Telescopes

Camera Bug is one of the largest telescope, binocular, and telescope accessory stores in the Southeast. We have actual on-site inventory and have been serving the astronomical community with over 25 years of experience. Product line includes Meade, Celestron, Orion, TeleVue, JMI, Astrozap, Kendrick, etc.....

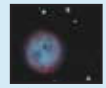
CAMERA BUG LTD

To order call: Order Line **1-866-422-6284**
404-873-4513/ Fax 404-873-3925
Camera Bug
Atlanta, GA

www.camerabug.com

Eyepieces / Accessories

There is a universe full of things to see and a maze of eyepieces to see them with.
We specialize in eyepieces. Check out our web site and call us for help in picking your way through the maze. How can a small company sell the same eyepieces at such great prices? We import directly and keep our overhead low.

Owl Nebula  **Chris Schur**

KNIGHT OWL EYEPIECES
To order call: **1-888-OWL-WARE**
(10 AM to 6PM EST) or use our website
owl1@owlservices.com

www.owlastronomy.com

More of everything you love about *Astronomy* magazine... online!

FREE Bonus Material

Astronomy.com

- More in-depth information about the stories in each issue
- Interactive mountaintop observing—a new mission every night
- Multimedia gallery of images, movies, and sounds to explore
- Weather tracking from your desktop
- Plus much more!

Subscribe today for these great benefits!

05X1098

CALL 800-533-6644
or visit astronomy.com
A5BA3A

marstalk

Here are some words commonly used by planetary scientists:

Aerobrake — a technique using friction from a planet's atmosphere to slow a spacecraft so the planet's gravity can capture it into orbit

Basalt — a dense, gray rock of volcanic origin — the most common type of solidified lava

Bedrock — solid rock under soil or loose rocks

Caldera — a large, basin-shape volcanic depression, typically formed when a volcano collapses after eruptions deplete its magma chamber

ARSIA MONS CALDERA
NASA/JPL/MSSS

Chaotic terrain — a distinctive region of jumbled and broken terrain

Chasma — a deep, elongated depression with steep sides

OPHIR CHASMA
NASA/JPL/USGS

Crater — a bowl-shape depression formed by impact or volcano

Deimos — Mars' smaller moon, measuring 4.7 by 3.8 by 3.2 miles (7.5 by 6.1 by 5.2 km) and orbiting the planet at an average distance of 14,580 miles (23,460 km)

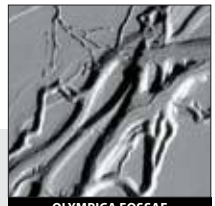
Deposition — the laying down of sediments by floods, glaciers, or other natural processes

Ejecta — material thrown out by an erupting volcano or a meteorite impact

Exobiology — the study of life on other planets

Fault — a break in a planet's crust, with the rock mass on one side of the break displaced from that on the other

Fossae — a long, narrow, and generally shallow depression



OLYMPICA FOSSAE
NASA/JPL/ASU

Geothermal activity — a surface event, such as a volcano or geyser, driven by a planet's internal heat

Hematite — an iron-rich mineral that usually forms in water

Mons — a mountain

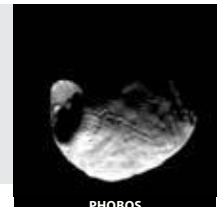
Outcrop — a section of rock exposed at a planet's surface

ENDURANCE CRATER OUTCROP
NASA/JPL/CORNELL

Palus — a small plain

Patera — an irregular crater, or a complex one with scalloped edges

Phobos — Mars' bigger moon, measuring 8.3 by 7.0 by 5.7 miles (13.4 by 11.2 by 9.2 km) and orbiting the planet at an average distance of 5,830 miles (9,380 km)



PHOBOS
NASA/JPL

Planitia — a low, broad plain

Planum — a plateau or high plain

Secondary crater — an impact crater formed when ejecta from another impact rains down

Sedimentary rock — formed from sediments deposited by water, wind, or ice

Sol — the length of a martian day, equal to 24 hours, 39 minutes, and 35 seconds

Vallis (plural Valles) — a valley

KASEI VALLIS
NASA/JPL/USGS

Yardangs — an aerodynamically shaped landform created through erosion by wind-blown sand

Astronomy magazine brings the universe down to Earth!

Larry Landolfi

Every issue of *Astronomy* magazine is packed with all the tools and information you need to enjoy the night sky. Whether you're a beginner or an experienced stargazer, *Astronomy* magazine can help you make the most of every minute under the stars!

- **TIPS** for locating stars, planets, and deep-sky objects
- **STUNNING IMAGES** that bring the universe to life
- Monthly pull-out **SKY CHART**
- Up-to-date **SPACE NEWS**
- Easy-to-understand **SCIENCE REPORTING**
- Exclusive **DIAGRAMS** and **ILLUSTRATIONS**

Subscribe today!

Call 800-533-6644

Mon-Fri, 8:30am-5:00pm CST
Outside the U.S. and Canada,
call 262-796-8776 x661

Or visit us on the web at
www.astronomy.com

BONUS: Subscribers get access to premium web content!

05X1076RH

A5B3A

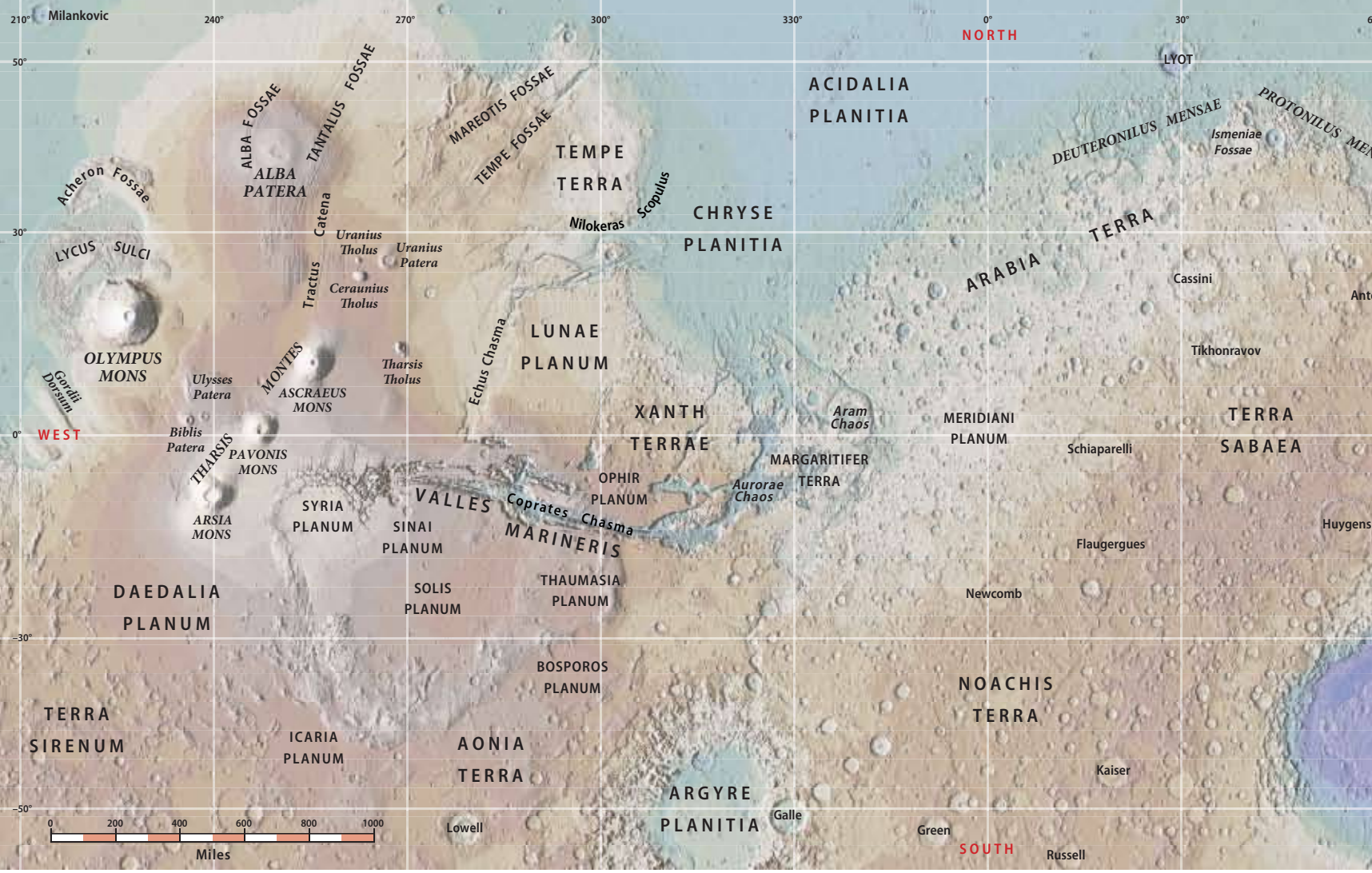
FOURTH from the Sun

The latest spacecraft are showing Mars more complex and fascinating than ever — and solving some long-standing mysteries.

BY ROBERT BURNHAM

Martian deserts glow warmly

ROCK



All across Mars' middle latitudes lie eroding sheets of material that look like they were deposited during storms unlike any on Earth, unless you combined a blizzard with a sandstorm.

So why go there?

Scientists reply that if Mars is hostile now, there once was a time — in its first billion years — when it was far more pleasant. It had a much thicker and more earthlike atmosphere, which led to both warmer temperatures and flowing water. The evidence for water is particularly compelling.

Dozens of river valleys and outflow channels trace where floods once poured across a jumbled landscape. The torrents carved their way through terrain, pooling in craters and depressions, then overflowed again to erode a path ever lower. Finally, the floods spread out across the bottom of a giant impact basin or the vast northern lowlands.

However life emerged on Earth, water was the key ingredient, and Mars shows ample evidence of water's traces. As far as scientists can tell, the geological stories of Mars and Earth in their earliest years were remarkably similar.

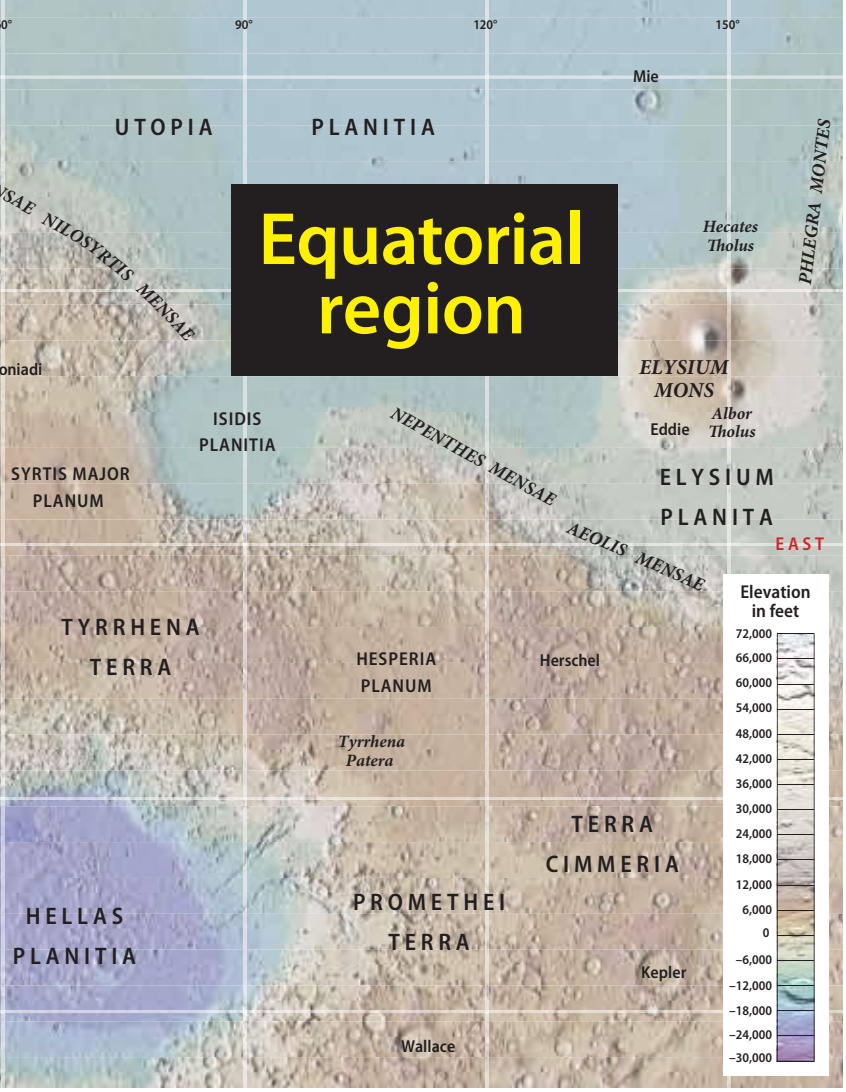
Since Earth has life, did Mars once, too? All of today's Mars research comes back to this so-far unanswered question. It's the kind of question whose answer will tell us a lot about our place in the solar system — and in the universe.

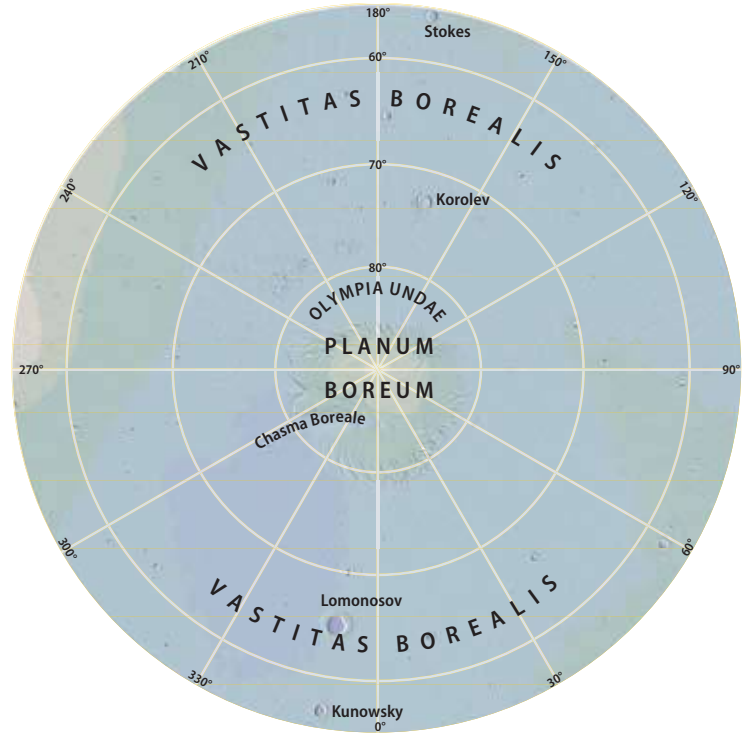
If Mars ever had living organisms, this second appearance of life in one planetary system would suggest life is likely in the universe, wherever conditions are right.

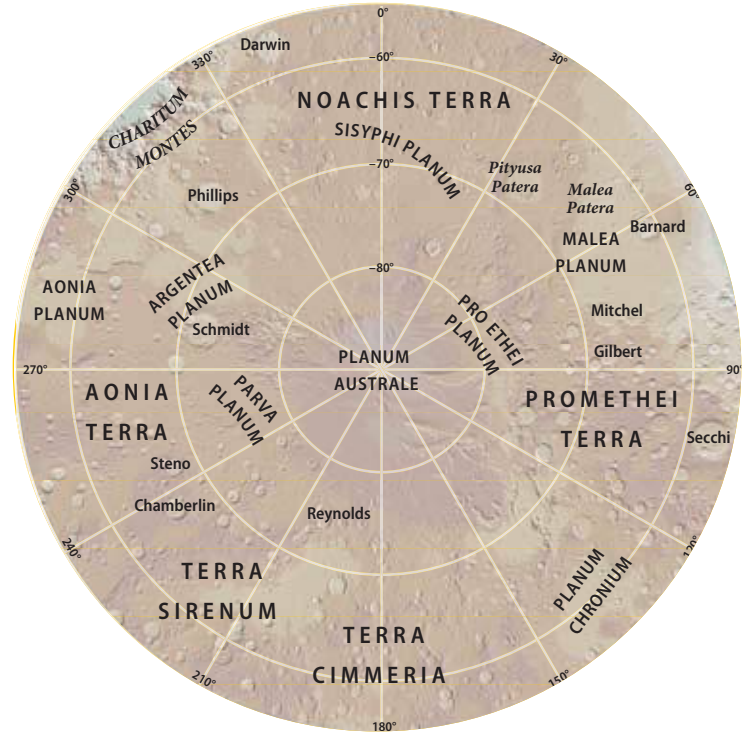
Mars is a terrestrial planet, the outermost of the Sun's major rocky bodies, orbiting on the inner edge of the asteroid belt. It takes 687 Earth days (668 martian days, or sols) to make one circuit of the Sun, following an orbit that ranges from 1.4 astronomical units (or AU; Earth orbits at 1 AU) when closest to the Sun (perihelion) to 1.7 AU at farthest (aphelion). Sunlight shines about 45-percent stronger at perihelion than aphelion.

Mars' polar axis inclines 25.2° to its orbit (Earth's tilts 23.5°). Thus Mars has four seasons, just as we do, although the elliptical martian orbit makes its seasons more unequal in length than ours. For example, spring in Mars' northern hemisphere is 41 days longer than the southern spring, which comes when the planet lies closer to the Sun.

As with Earth, Mars' polar axis precesses, swinging around in a circle. In Mars' case, the axis takes 175,000 years to complete the circle, compared with Earth's 26,000 years. The polar-axis tilt, now 25.2°, varies from 15° to 45°. Mars' orbital eccentricity also swings through a cycle, changing its perihelion position to the other side of the Sun every 36,000 years.







▲COMPARED WITH EARTH, the landscape of Mars looks almost simple because it lacks ongoing plate tectonics. Yet it contains big puzzles. For one, why are the two volcanic areas, Tharsis and Elysium, directly opposite the two big impact basins, Hellas and Argyre? USGS

Scientists can calculate how these effects drive long-term climatic changes on Mars, starting and ending ice ages, for example.

Earth's elevations span from the Marianas Trench 7 miles (11 km) below sea level to the summit of Mt. Everest, 5.5 miles (8.8 km) above. Mars has no "sea level" — instead, planetary scientists use a mean radius of 2,106 miles, or 3,390 km — but Olympus Mons reaches 14 miles (22 km) high, a range that slightly exceeds Earth's.

While Mars is a bit more than half Earth's size, by coincidence, its surface area matches our planet's land area. This underscores the scientific difficulties Mars poses. It is indeed a small object in solar system terms, but geologists are still a long way from a full understanding of Earth, a planet they can explore firsthand.

Approaching Mars in a spaceship, astronauts would see its tawny globe swelling steadily, with either or both polar caps gleaming white. The planet's distinctive color comes from rust.

Mars formed with many of the same materials as Earth: silicates and oxidized minerals of iron and magnesium. When the abundant

iron in the martian crust rusted and broke down into dust, it tinted the whole planet's surface.

As the astronauts approach Mars, they would see the wide scar of Valles Marineris, Mars' "Grand Canyon," slowly rotate into view. This rift valley, 2,500 miles (4,000 km) long and 4.5 miles (7 km) deep, outsizes our Grand Canyon about tenfold. Valles Marineris stretches around a fifth of Mars; if placed on Earth, the feature would span the whole United States. And if scaled up to fit Earth as it does Mars, we would have a 10-mile-deep gash running across the United States *and* the Atlantic Ocean.

The western end of Valles Marineris dissolves into a tangled terrain of intersecting blocks, which carries the appropriate name of Noctis Labyrinthus, the labyrinth of night. The blocks merge and blend into the volcanic landscape of Tharsis, home to Olympus Mons and four other gigantic volcanoes: Arsia Mons, Pavonis Mons, Ascraeus Mons, and Alba Patera.

While these are not the only volcanoes on Mars — a smaller volcanic area lies in Elysium, almost half the planet away — collectively, the eruptions that created Tharsis raised a 6-mile-high (10 km) bump of lava on one side of Mars. What caused the birth and growth of Tharsis, and why it remains a solitary feature, is a first-rank geological puzzle.

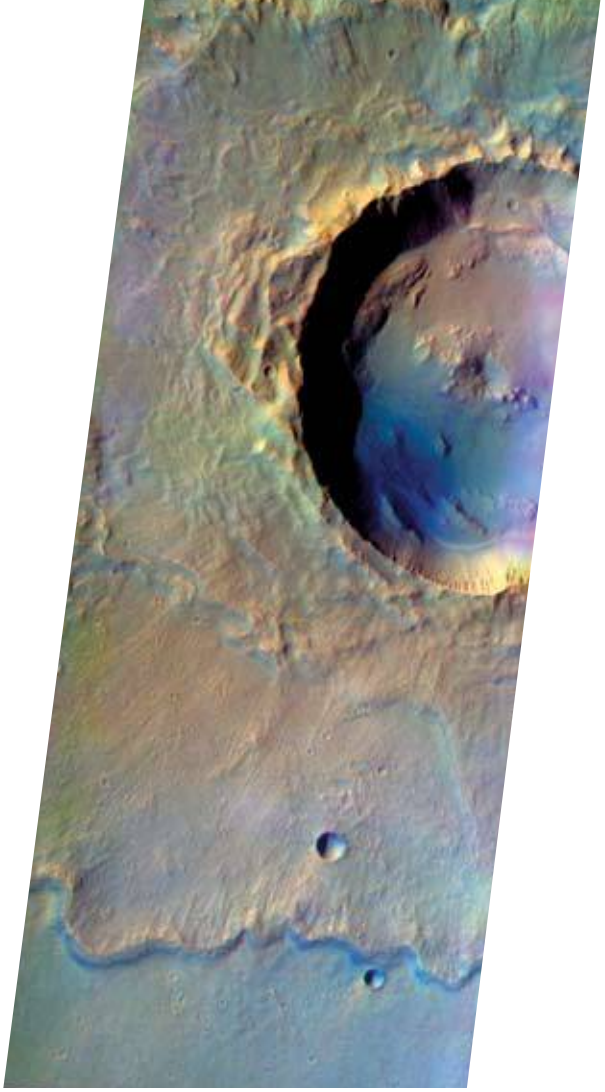
▲ **FAULTING CREATED COPRATES CHASMA, the trough dominating this image's center. Located in Valles Marineris, Coprates Chasma digs 5 miles below the surrounding plains.** ESA/DLR/FU BERLIN (G. NEUKUM)

At the eastern end of Valles Marineris, and from its northernmost rift, winding channels lead toward a huge lowland plain. This expanse lies 3 to 4 miles (6 km) lower than the cratered highlands to the south. When Mariner 9 images revealed the channels in 1971, scientists recognized immediately that Mars has seen catastrophic flooding and has not always been a cratered desert.

Researchers now think when faults opened as the giant Tharsis volcanic province grew, they released groundwater that cascaded through what is now Valles Marineris. This collapsed the valley walls and set off gigantic floods dwarfing anything on Earth. The flood waters rocketed into the northern lowlands, leaving behind chaotic terrain and channels with islands that still show streamlining. When the water reached the lowlands, it likely pooled and formed, at least for a while, an "Oceanus Borealis."

Why one hemisphere of Mars should contain a gigantic lowland plain is another unsolved geo-puzzle. As the maps on pages 10 and 11 show, the lowlands are eerily flat across hundreds of miles.

With the lowlands appearing largely uncratered, scientists once saw the expanse as relatively recent, at least in geological terms. All



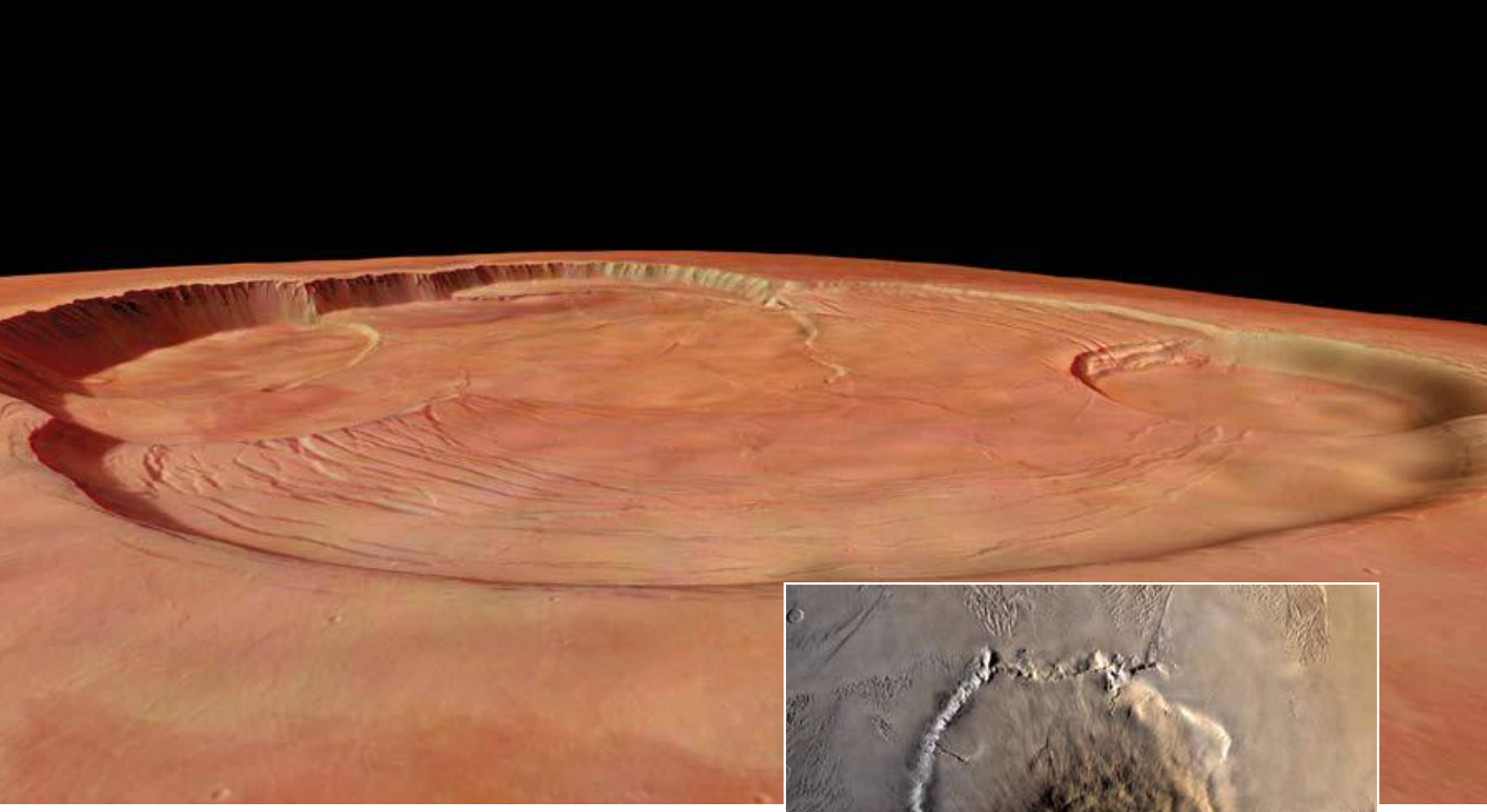
▲WATER IN THE GROUND helped build the apron around this 13-mile-wide crater in Chryse Planitia. Scientists theorize water mixed with the rocky ejecta, causing it to flow in lobes. NASA/JPL/ASU

▶A JUMBLE OF CRUSTAL BLOCKS, Aureum Chaos formed when groundwater or ice melted, perhaps caused by geothermal activity. As the water flowed away, the ground collapsed. ESA/DLR/FU BERLIN (G. NEUKUM)

else being equal, older surfaces on planets or moons bear more craters because they've been exposed longer and have suffered more meteorite impacts. A lack of craters signals geological youth.

But the idea of the lowlands being young suffered a blow when researchers found subtle traces of heavy cratering under the smooth surface. These craters have been all but obliterated by lava that covered the lowlands more recently. Thus the lowlands are an *ancient* feature, created perhaps by global tectonic activity back when Mars' dense iron core was hotter and the planet more geologically active.

Supporting the notion of an early, active core are remnants of magnetism found in the southern hemisphere's crustal rocks. At the time the rocks formed, they took on the signature of the existing magnetic field. This field later dwindled and vanished as the core cooled below a critical point that turned off the planet's internal dynamo, leaving the terrain's magnetism as its only testimony.



▲ **THE SUMMIT CALDERA on Olympus Mons spans about 45 miles and is 2 miles deep.** ESA/DLR/FU BERLIN (G. NEUKUM)

When astronomers were stuck on Earth, peering through telescopes, Mars presented only the coarsest global features. As generations of spacecraft provided sharper and sharper views, however, the level of detail has exploded. The two rovers currently on Mars, Spirit and Opportunity (see pages 62–93), have taken this to an extreme, providing clear views of rocks and sand barely a fraction of an inch across.

But even with a long operating life, a rover can see just so much of Mars. The main task of collecting data to interpret the planet has fallen to orbiters — spacecraft that also peer through telescopes, but from distances of only a couple hundred miles. Like aerial photos of Earth, spacecraft images let researchers study martian landscapes in detail.

Due for arrival in March 2006 is the latest in the series, the Mars Reconnaissance Orbiter, or MRO (see page 94). Built to locate outcrops of rocks laid down in water that could contain life's traces, MRO's cameras will neatly span the size range of features seen by the rovers and that seen by previous orbital cameras.

All of our Mars spacecraft — and others to come in the years ahead — are built to further NASA's strategy in hunting for life (or its traces). This strategy is easy to describe — "follow the water" — but if the strategy appears simple, the task is not.

Starting when Mariner 4 flew past Mars in 1965 and shattered Percival Lowell's vision, replete with its canals and Martians, each

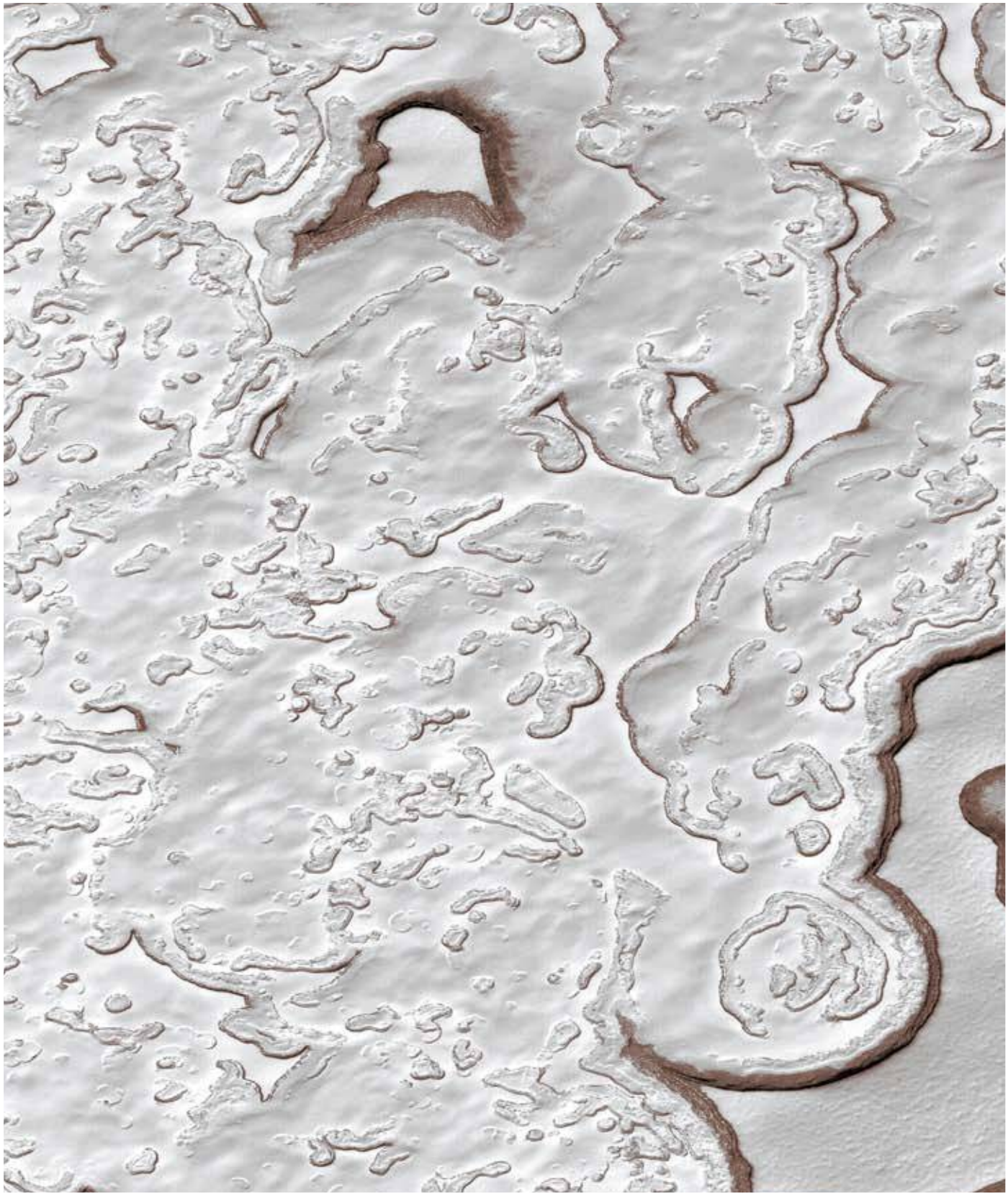
▲ **OLYMPUS MONS is the highest volcano in the solar system and was built by many thin flows of lava. The summit rises about 14 miles above the plains, and the base (scalloped by landslides) spreads almost 400 miles across — the width of Arizona.** NASA/JPL

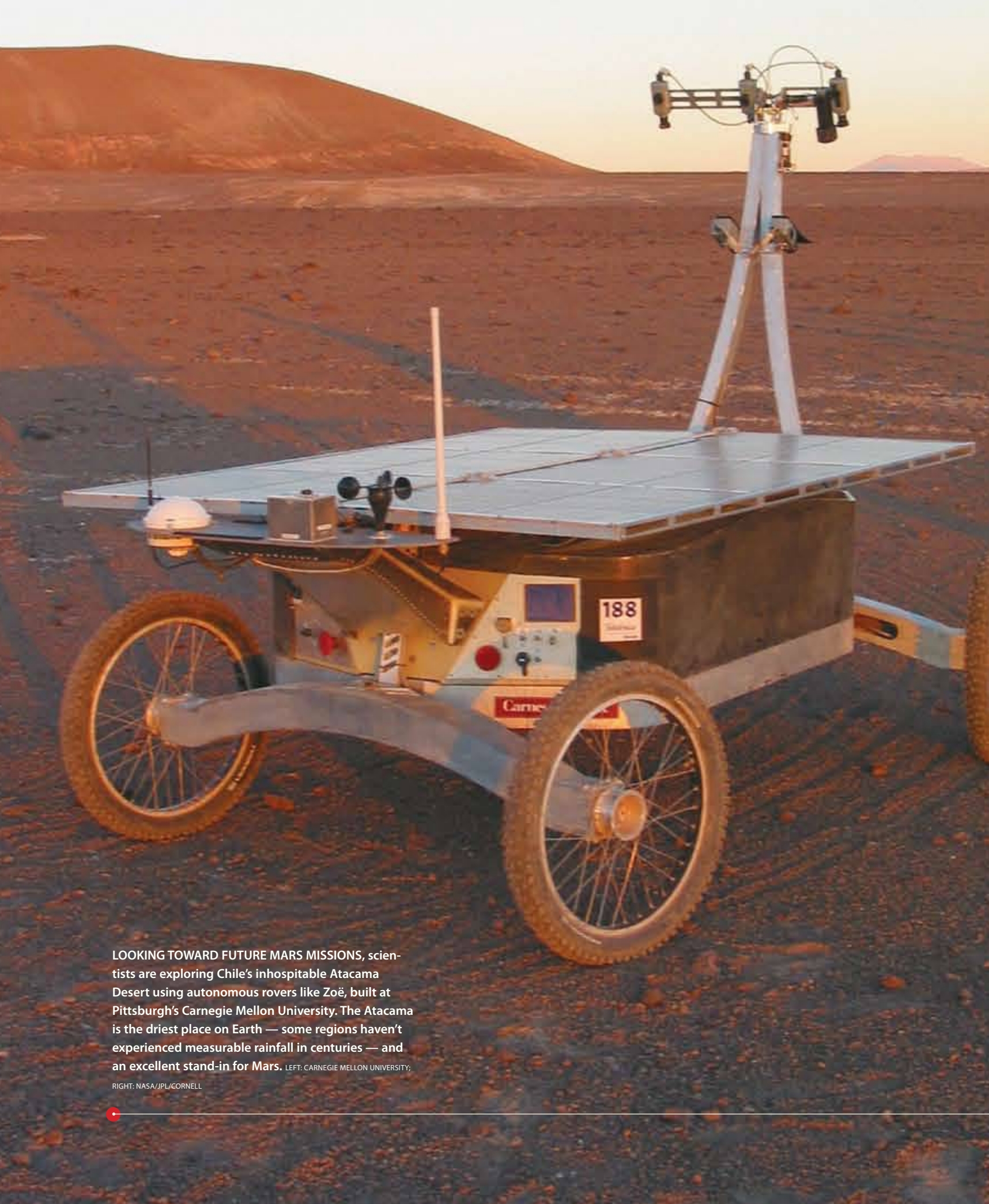
mission since has shown the Red Planet to be more complex and mysterious than scientists thought. No one should be astonished that surveys of Mars raise more questions than they answer. Mars is a fully developed world whose history partly parallels ours, but diverged from it early on.

As we seek to understand our place in the Sun's family and our origins, Mars holds crucial pieces of evidence. In sending orbiters to scrutinize Mars from above, and landers to study its surface at short range, we gradually open up our own planet's history — at least in a comparative sense.

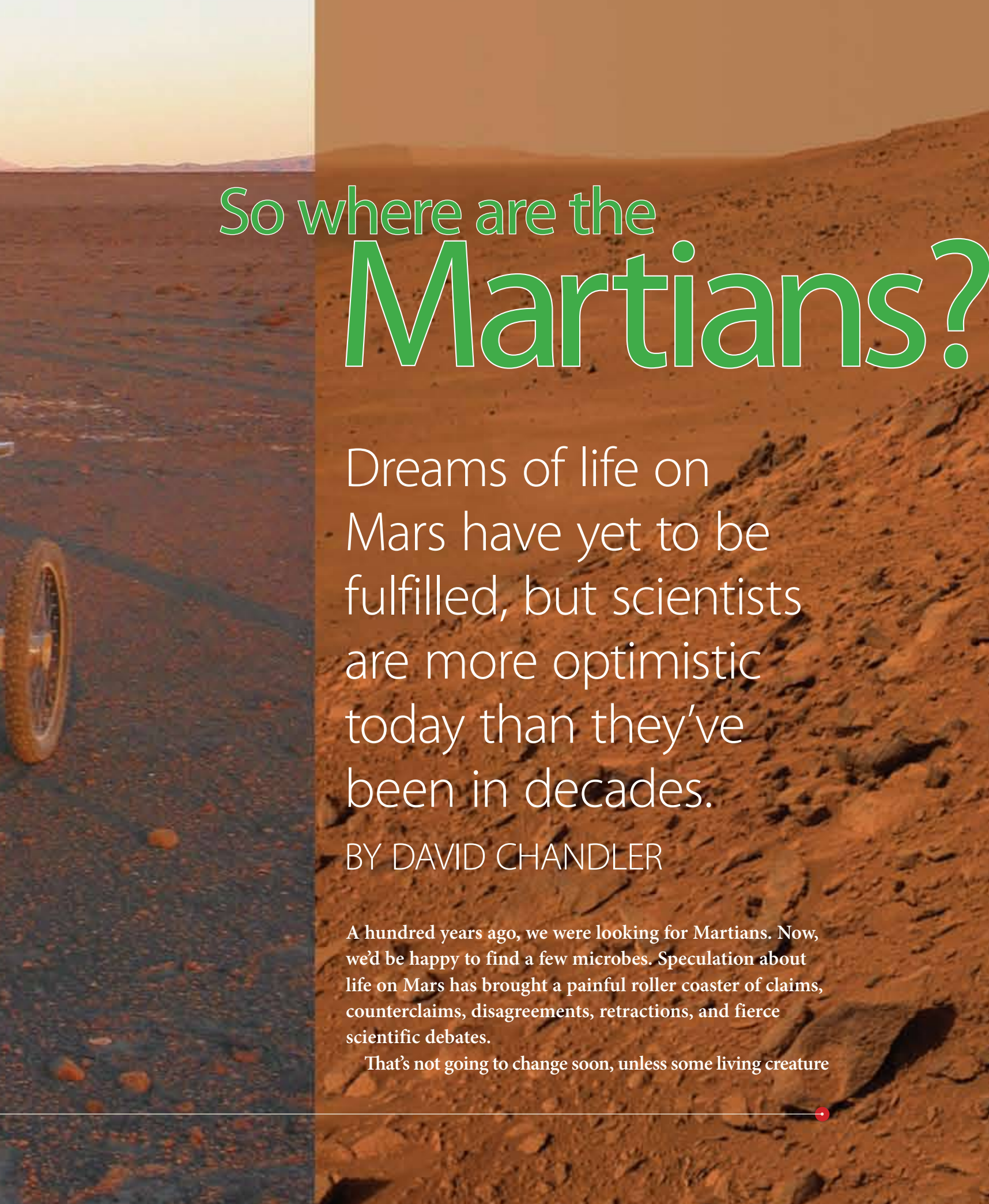
And in so doing, we are discovering ourselves.

Robert Burnham *is a senior editor of* Astronomy.





LOOKING TOWARD FUTURE MARS MISSIONS, scientists are exploring Chile's inhospitable Atacama Desert using autonomous rovers like Zoë, built at Pittsburgh's Carnegie Mellon University. The Atacama is the driest place on Earth — some regions haven't experienced measurable rainfall in centuries — and an excellent stand-in for Mars. LEFT: CARNEGIE MELLON UNIVERSITY; RIGHT: NASA/JPL/CORNELL



So where are the Martians?

Dreams of life on Mars have yet to be fulfilled, but scientists are more optimistic today than they've been in decades.

BY DAVID CHANDLER

A hundred years ago, we were looking for Martians. Now, we'd be happy to find a few microbes. Speculation about life on Mars has brought a painful roller coaster of claims, counterclaims, disagreements, retractions, and fierce scientific debates.

That's not going to change soon, unless some living creature

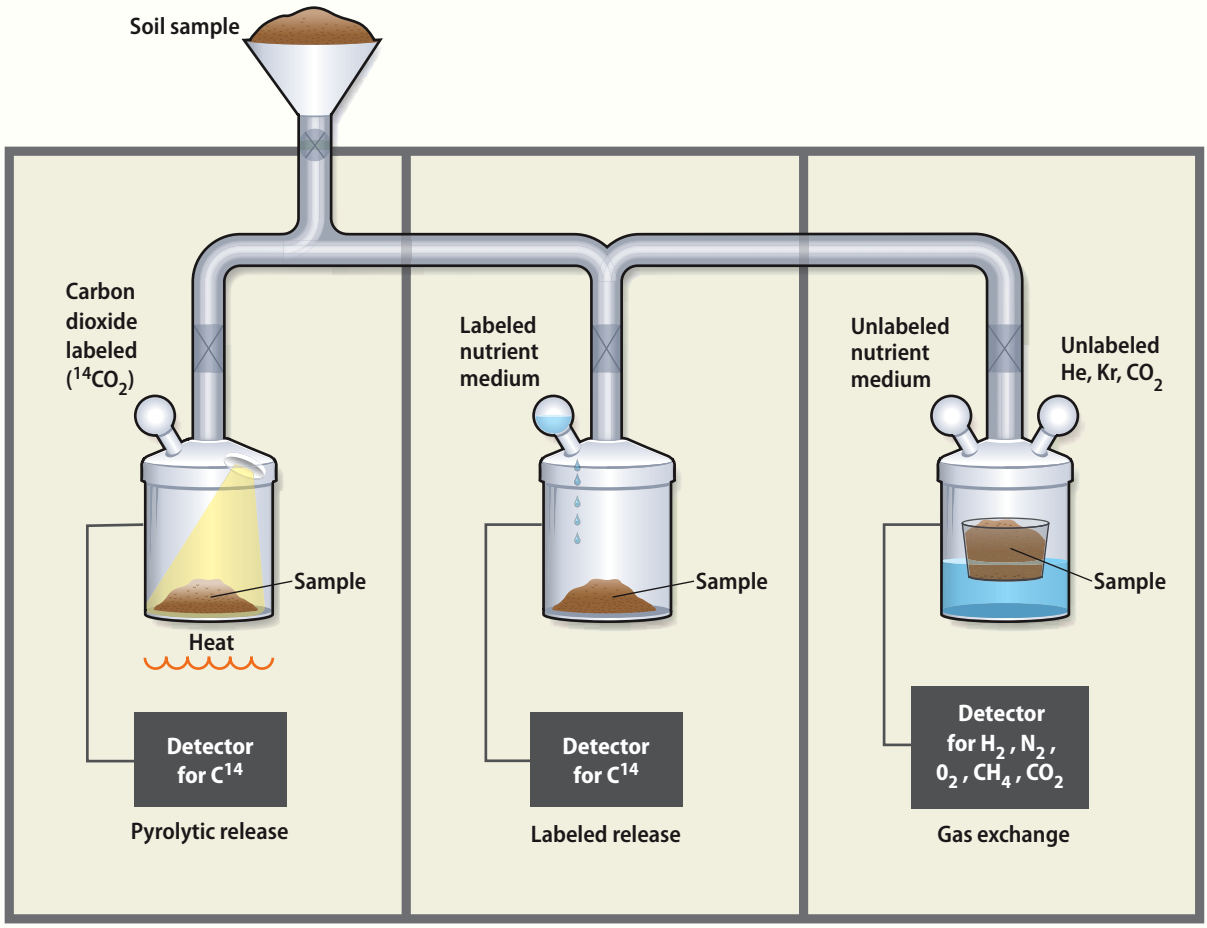
THIS VIKING ORBITER scene shows the southern Chryse basin, where massive outflow channels testify that fluid once flowed on Mars. The channels, originating in jumbled terrain at the bottom (south), flow north and empty into the Chryse plains. "Follow the water" has been the paradigm for Mars exploration since Viking. NASA/U.S. GEOLOGICAL SURVEY

walks in front of one of our robotic eyes on Mars. For now, the debate gets more intense with every new finding.

And yet, there has been a sea change in scientific opinion. It's one of those turning points where an idea goes from being heresy to being a new paradigm in which researcher disagreement lies mostly in the details. One sign of that change was a European Space Agency meeting in February 2005, when an informal poll of 250 scientists showed 75 percent believe that life has existed on Mars. Although there had been no similar poll in earlier years, this result is clearly a major leap from what before had been a minority position.

And even more dramatically, 25 percent of those scientists think life is still there today. Even a year ago, anyone who thought that most likely wouldn't have dared to say it at a scientific meeting.

Looking for life, Viking style



▲ **THE THREE VIKING BIOLOGY EXPERIMENTS** each involved the incubation of martian soil samples under controlled conditions. The pyrolytic-release experiment (left) used radioactive carbon-14 (C^{14}) added to the test's martian atmosphere to look for molecules living organisms built. The labeled-release experiment (center) delivered water and nutrients laced with C^{14} to each sample. It looked for increased radioactivity as living organisms consumed the nutrient and released radioactive waste gases. The gas-exchange experiment (right) monitored how concentrations of biologically important gases changed when each sample was given nutrient- and C^{14}-enriched water. *ASTRONOMY*: THEO COBB

▲ **THE VIKING 1 LANDER'S** robot arm scooped up martian soil and delivered samples to an instrument package containing a series of biological tests. The Viking biology package was the only such experiment ever flown to Mars. Each test searched for signs of metabolism from living organisms. NASA/JPL

▲ ZOË'S VIEW of the Atacama Desert, built from a mosaic of camera images, resembles panoramas of Gusev Crater and Meridiani Planum returned by Spirit and Opportunity — except for the blue sky.

CARNEGIE MELLON UNIVERSITY

What a difference evidence for flowing and standing water, plus a whiff of methane, can make.

Liquid water seems to be a prerequisite for every kind of life known, and it's hard to imagine a convincing alternative. So the guiding refrain of NASA's search for life elsewhere has been to follow the water. And on Mars, that dowsing venture has been an unexpected success.

Few people doubted Mars once had water. Images returned by Mariner 9 (1971–1972) and the Viking orbiters (1976–1980) revealed sinuous, branching channels that look like terrestrial riverbeds. But there still were arguments. It took the chemical and mineralogical tests of the twin Mars rovers in 2005 to prove liquid water once coursed across the martian landscape.

So the most basic prerequisite of life was indeed present. And energy in the form of sunlight, as well as geothermal heat, also are present, although both at much lower levels than on Earth. Yet Mars does have unique problems where life is concerned.

The two biggest problems are ultraviolet radiation and the near vacuum of the surface. Andrew Schuerger, a microbiologist with Florida State University, has studied the survival of terrestrial microbes under martian conditions, to figure out whether we might have inadvertently contaminated Mars with stowaway microbes on our landers and rovers. Despite thorough sterilization of all Mars-bound craft due to strict planetary protection rules, inevitably some microbes survive and make the trip.

Schuerger's studies provide good news. The martian atmosphere's 6-millibar surface pressure, far thinner than on the highest terrestrial mountaintop, is very quickly lethal to Earth bugs. The low pressure kills off even microbes shielded deep inside nooks and crannies.

This is a good thing for today's scientists who hope to conduct tests to search for possible signs of life on Mars. The last thing they would want is to detect signs of life that turn out to be contamination from earlier missions.

Many people are under the impression the Viking missions in 1976 already settled the question of whether Mars has life, but, in fact, its biology experiments gave ambiguous findings. The final peer-reviewed report on the mission says the results of one of its three tests met all the agreed-upon criteria for a positive result.

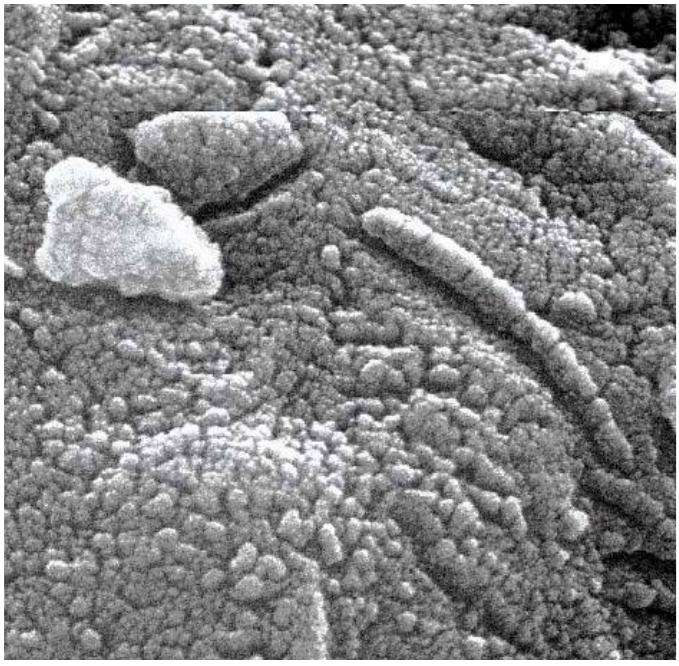
Gilbert Levin of Spherix Inc. in Beltsville, Maryland, was the lead scientist for Viking's labeled-release experiment, and he has always maintained the test's results were positive. In 1999, Levin published his conclusion that, based on the accumulated evidence since then, the Viking landers' biology experiment had, in fact, detected martian life.

Few others accept this conclusion, largely because of perplexing results from another Viking instrument, one designed to identify molecules in the soil. It failed to find any sign of organic molecules, considered a prerequisite for life, which seemed to negate the biological interpretation of the labeled-release test. Most scientists decided extremely reactive chemicals — peroxides, superoxides, or others — present in the soil could explain the puzzling results.

But no such chemicals have been detected, nor has anyone yet fully duplicated the test results in a lab using any such chemical concoction, Levin points out. Moreover, because the device's threshold of detection was so high, many microbes could be present and go undetected.

What would it take to convince skeptics? One simple follow-up test that could have clinched the issue never got the chance: It was lost in 1996 when the Russian Mars 96 craft crashed in South America just three Earth orbits after launch.

This test would have looked for a different response to a nutrient solution, depending on whether left- or right-handed versions of nutrient were fed to the soil. Chemical reactions use each version equally, but living organisms use only right-handed molecules.



◀**POSSIBLE FOSSIL BACTERIA in martian meteorite ALH84001 (see photo below) consist of minute elliptical, rope-like, and tube-shape structures found in fractures within carbonate mineral grains. These structures, just tens of nanometers (billionths of a meter) across, can be seen only with an electron microscope. However, most scientists think earthly contamination and non-biological chemistry best explain this evidence. ALH84001 raises a fundamental question: Will we be able to identify life if we see it?** NASA/*SCIENCE*//McKAY ET AL.

▼**ALH84001 IS THE ROCK that reinvigorated the debate over martian life. A meteorite impact blasted it from Mars about 16 million years ago. It landed in the Antarctic 13,000 years ago, where it lay in ice until scientists recovered it in 1984. In 1996, NASA scientists argued that microscopic fossil-like structures and certain minerals point to past life on Mars. The carbonate grains enclosing this evidence — themselves barely visible to the unaided eye — represent less than 1 percent of the rock.** NASA/*SCIENCE*//McKAY ET AL.

In the same year, the next tantalizing glimpse of possible life on Mars hit the news. This time, it was possible evidence of past microbial life preserved inside a martian meteorite found in Antarctica. The rock contained organic molecules and unusual magnetite crystals suggesting a biological origin, according to a team of researchers at NASA's Johnson Space Center in Houston.

The team has continued its work on the meteorite, dubbed ALH84001, and in 2005, published new findings that seem to strengthen the case for a biological origin. Other groups have claimed non-living chemical processes can explain all the features found in the rock, and there is still no consensus at all on the significance of microscopic formations within the meteorite. A din of dispute and disagreement surrounds the meteorite evidence, a fate shared with many previous claims of evidence for Mars life.

In the meantime, scientists are developing new ideas on how to search for life. One team of robotics engineers from Carnegie Mellon University in Pittsburgh, in collaboration with scientists from NASA's Ames Research Center in Moffet Field,

California, has developed a prototype Mars rover — named Zoë — with advanced life-detection capabilities.

The key to Zoë's success is a set of specially formulated marker dyes. Sprayed on the ground, the dyes fluoresce in the presence of important biological molecules when energized by a strobe light's flash. A CCD camera picks up any fluorescence, as well as the natural glow chlorophyll emits in bright light.

In the shade of the rover's body, the brief flash and short exposure time let Zoë's camera detect the faint response even in

▲ZOË DETECTS LIFE with the help of fluorescent dyes that bind to chlorophyll, DNA, proteins, and carbohydrates. Alan Waggoner, Atacama team member and director of the Molecular Biosensor and Imaging Center at Carnegie Mellon, squirts dye on a sample area beneath Zoë's fluorescent imager — a task now done without human intervention. When energized by a flash of light, the dyes glow at specific wavelengths, and Zoë captures an image. Zoë's 2004 field tests marked the first time rover-based automated technology identified life in the Atacama Desert. CARNEGIE MELLON UNIVERSITY

broad daylight. In Chile's Atacama Desert, American scientists guided the rover remotely using only information transmitted by its own instruments. Zoë succeeded in detecting life even in the most desiccated regions of Earth's driest desert.

That's a promising start toward something that might work on Mars. Zoë will conclude its third season of Atacama field tests this fall. "This year we'll be able to see how densely an area is populated with organisms and map their distribution," says Carnegie Mellon's David Wettergreen, who leads the project. "This is the first time a robot is looking for life," he says. "We are working toward full autonomy of each day's activities, including scheduling time and resource use, and navigation between study areas."

In the Atacama's driest zones, life stands its best chances beneath the surface rather than on it. If this is also true for life on Mars, scientists may have to go drilling to find it.

Steven Gorevan, a member of the Mars Exploration Rover science team, has been working on an automated deep-drilling rig for a future Mars mission. And Carol Stoker of NASA Ames has been searching for the kinds of exotic life-forms that could exist under harsh conditions that prevail on parts of Mars — intermittently wet, with highly acidic and very salty water.

At Rio Tinto in Spain, Stoker and her team drilled down more than 100 yards below the surface and found at least four previously unknown types of organisms living there. The organisms subsist on chemical energy, completely independent of sunlight or oxygen, and produce methane as they go about their metabolic business.

The Opportunity rover may have discovered a similar type of environment at Meridiani Planum. Such organisms clearly could survive under the surface of Mars even today. So the discovery of such forms of life on Earth — with expanding evidence for an early, wet Mars and the presence of methane in today's martian atmosphere — adds up to the tantalizing possibility that life exists beneath the martian surface.

Like so many other discoveries suggestive of life, the detection in 2004 of methane in martian air provokes disagreement both as to what was found and what it might mean.

Three separate groups each have found more-or-less consistent amounts of martian methane. Two used ground-based telescopes, and one used a spectroscope aboard the European Space Agency's Mars Express orbiter.

On Earth, organisms, both living and decaying, produce most of the methane. On Mars, the gas persists in the atmosphere only for a few centuries. So, if the Red Planet's atmosphere holds methane, somehow the gas must be replenished.

Life isn't the only possibility, of course. Scientists say a recent comet impact, volcanic eruption, or ongoing geothermal activity might explain the small amounts of methane detected. Individuals on two of the three teams making the detection claim the activity of martian microbes is the most plausible explanation. But most scientists — even others on those teams — think the answer lies in martian geology, not biology.

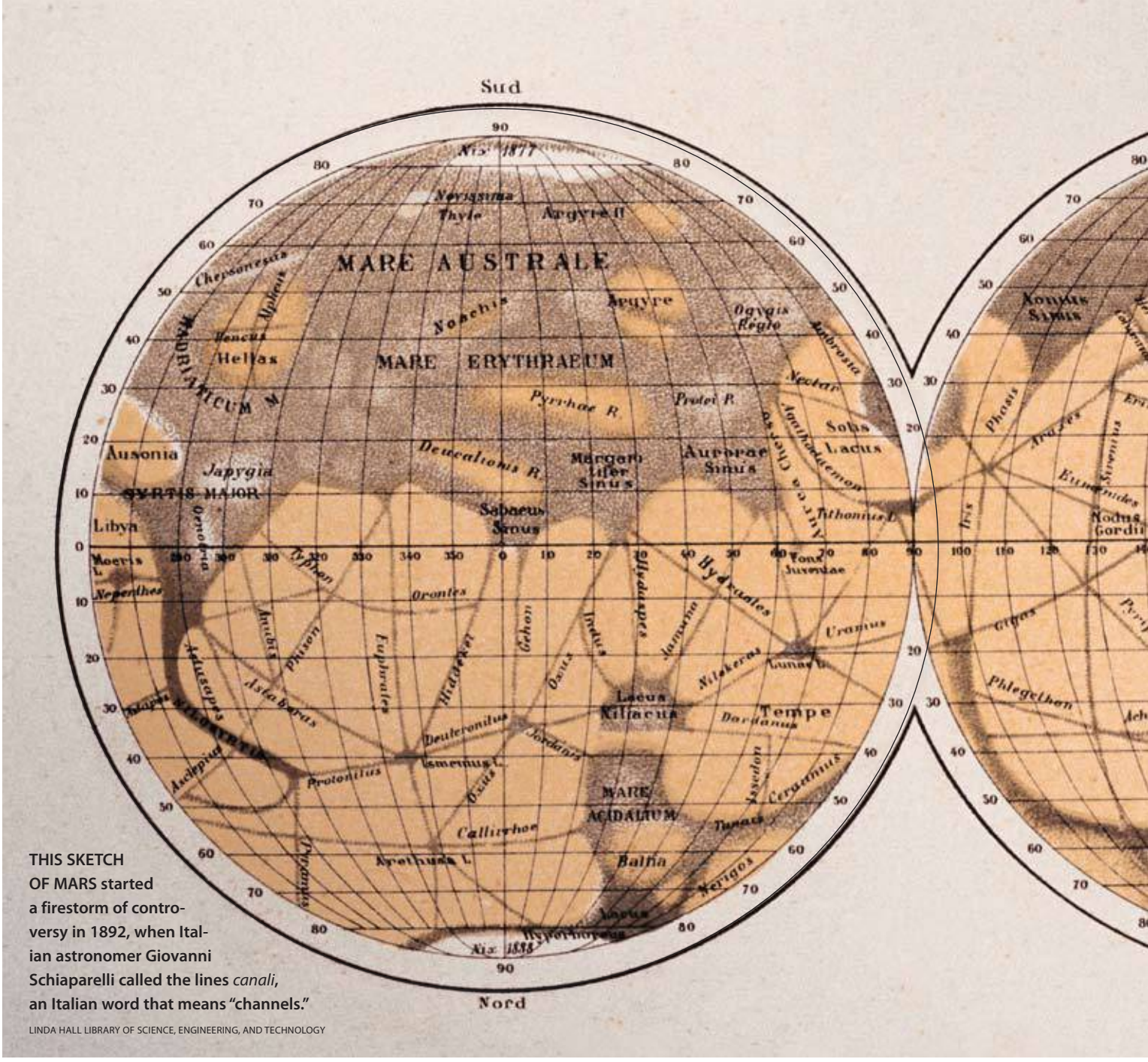
The elusive proof is still not there, and skeptics remain doubtful.

Is there life on Mars? This question won't likely be answered for a long time, if only because no planned or upcoming missions carry a life-detection experiment. But perhaps NASA will include such a test in the still-unchosen experiment package for Mars Science Laboratory, a rover scheduled for launch in 2011. If so, after hundreds of years of wondering, we will finally get the answer.

▲LIFE ON EARTH thrives in some of the least-expected places. In 2005, University of Colorado scientists Jeffrey Walker, John Spear, and Norman Pace discovered microbes living in the pores of rocks in one of the hottest and most active geysers at Wyoming's Yellowstone National Park. The Norris Geyser microbes thrive in 95° F (35° C) water acidic enough to dissolve nails. NSF

▲THE THIN GREEN LINE in Norris Geyser rocks is a new species of cyanidium algae. These microscopic plants are among the most acid-tolerant organisms known. Because the plants become incorporated into the rock, they'll leave fossil imprints behind. Rocks in what were once hydrothermal environments on Mars may be the best place to find fossil evidence of past life there. NSF

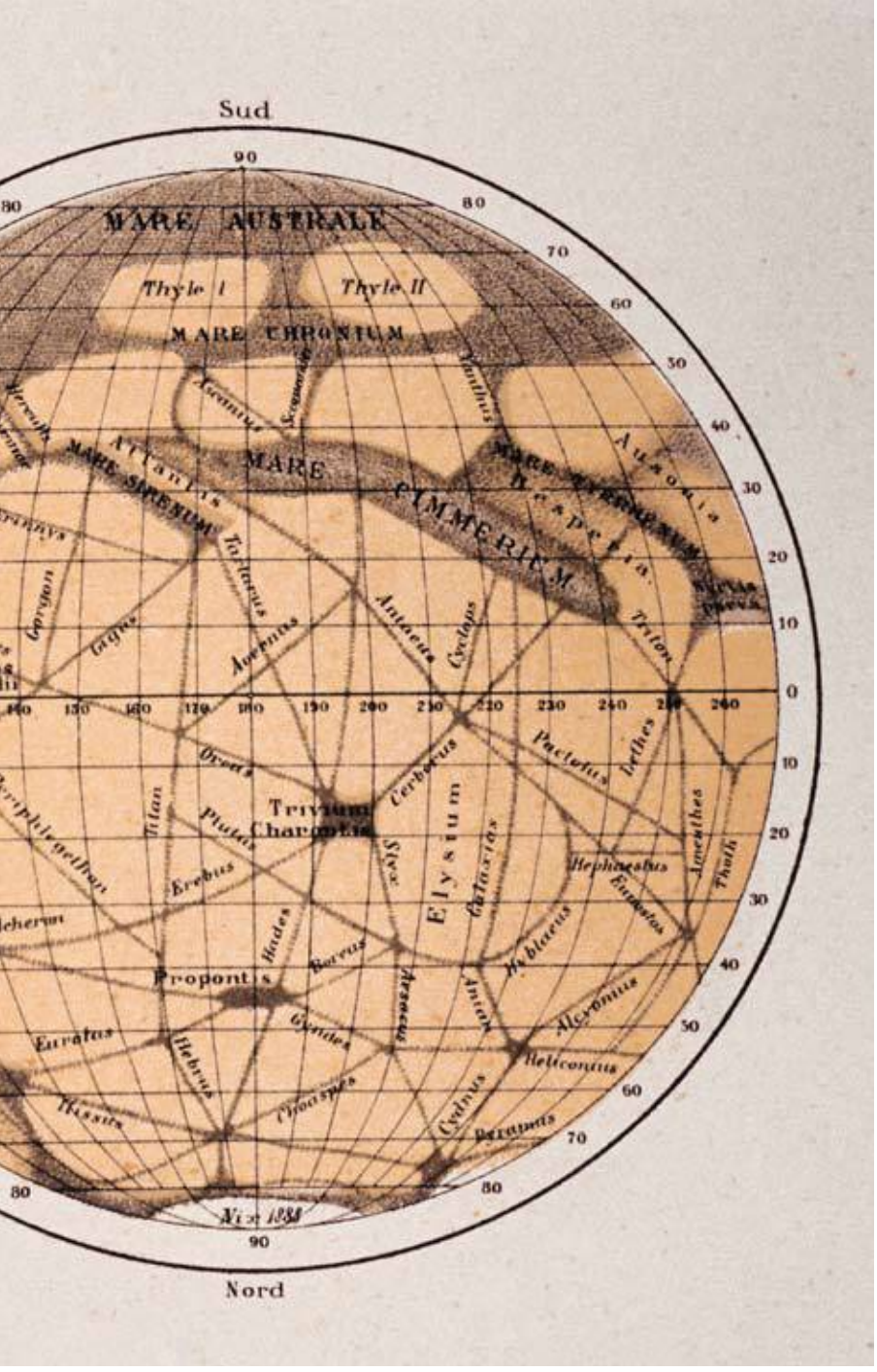
David Chandler *is a freelance writer. He covered science and space exploration for the* Boston Globe *for 20 years and is working on a book about the search for life beyond Earth.*



THIS SKETCH OF MARS started a firestorm of controversy in 1892, when Italian astronomer Giovanni Schiaparelli called the lines *canali*, an Italian word that means "channels."

LINDA HALL LIBRARY OF SCIENCE, ENGINEERING, AND TECHNOLOGY

Before the SPACE



In the years before spacecraft probed the martian surface, observers could see little more than bright and dark markings

AGE

Mars is full of surprises.

observers thought they saw vast areas of vegetation on the Red Planet's surface. In the years before spacecraft, martian surprises often had more profound implications.

In the 1890s, observers peering through telescopes glimpsed lines seemingly etched across Mars' shimmering ochre disk, igniting controversy over the existence of extraterrestrial life. Since then, the hopeful expectations we held for telescopic exploration set us up for the biggest surprise of all when the first robotic spacecraft reached Mars in 1965.

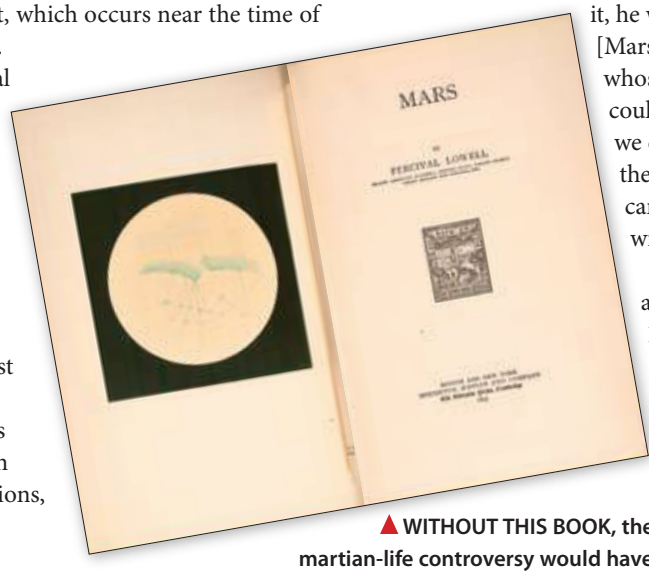
The history of telescopic Mars exploration followed a cycle dictated by the orbits of Earth and Mars. Every 26 months, our planet moves between Mars and the Sun. At these times, the Red Planet rises at sunset and shines brightly throughout the night. Astronomers call this alignment, which occurs near the time of closest approach, an opposition.

Because Mars has an elliptical orbit, its opposition distance varies greatly, from a minimum of 35 million miles (56.3 million kilometers) to a maximum of 60 million (96.6 million km). About every 15 years, the planet is brilliant at opposition because it nears the point in its orbit where it's closest to the Sun (perihelion). During such perihelic oppositions, Mars appears up to 7 times larger than during distant (aphelic) oppositions, enabling observers to discern tantalizing details on its surface.

Using ever-improving telescopes, 17th- and 18th-century astronomers slowly revealed Mars' basic properties. In 1610, Galileo began the telescopic exploration of Mars by discovering the planet showed a disk. Fifty years later, Dutch astronomer Christiaan Huygens charted the first surface feature seen on Mars — the triangular dark patch Syrtis Major. In 1666, Huygens' colleague Giovanni Cassini spotted the planet's bright white polar caps and determined its day length — about 24 hours, 40 minutes.

By 1784, English astronomer Sir William Herschel had determined Mars' axial tilt is similar to Earth's; thus, Mars has seasons. He noted the polar cap in the winter hemisphere grew as the one in the summer hemisphere shrank. Herschel's observations bolstered the belief that Mars was a world like Earth. Reporting a martian atmosphere, he said, "its inhabitants probably enjoy a situation in many respects similar to ours."

In the century after Herschel, astronomers drew the first comprehensive maps of the Red Planet, but little new data emerged to confirm or deny Herschel's inhabited, earthlike Mars. Then came the perihelic opposition of 1877.



▲ **WITHOUT THIS BOOK, the martian-life controversy would have been only a footnote of historical astronomy. But when Percival Lowell authored *Mars* in 1895 (along with two subsequent works about life on the Red Planet), the general public became interested, and other astronomers felt compelled to refute Lowell's findings.** MICHAEL E. BAKICH COLLECTION

Astronomers around the world reported new discoveries. At the U.S. Naval Observatory in Washington, D.C., Asaph Hall discovered Mars' two small moons Phobos and Deimos. Meanwhile, in Italy, Giovanni Schiaparelli sketched what he saw through his 8.6-inch refracting telescope. He gave the martian features evocative ancient Greek and Latin names, and he recorded many straight lines. Schiaparelli dubbed the lines *canali*, which in Italian means "channels" or "grooves." English speakers mistranslated the word as "canals," a term that implies artificial construction.

During the unfavorable oppositions of the 1880s, other observers also claimed to have glimpsed canals, although most professional astronomers remained skeptical of their existence. In 1892, French astronomer Camille Flammarion mapped a dense canal network and published his popular book *La Planète Mars*. In it, he wrote: "It would be wrong to deny that [Mars] could be inhabited by human species whose intelligence and methods of action could be far superior to our own. Neither can we deny that they could have straightened the original rivers and built a system of canals with the idea of producing a planet-wide circulation system."

Flammarion's book became a best-seller around the world. On Christmas Day, 1893, a copy reached wealthy Bostonian Percival Lowell.

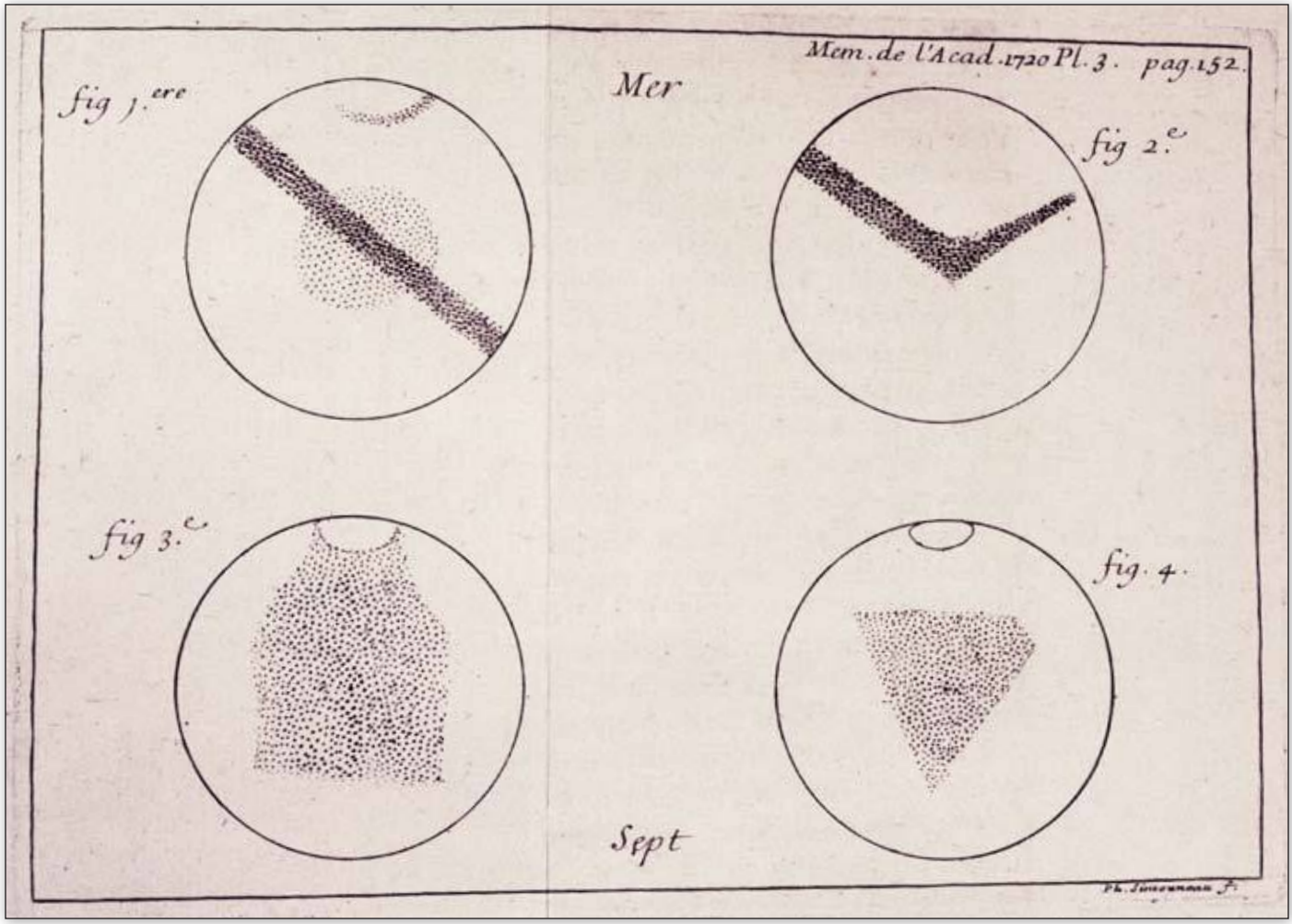
During the previous decade, Lowell had traveled in the Far East, and even had facilitated diplomatic relations between the United States and Korea. Now he turned to the concept of an advanced civilization on distant Mars.

Within 2 weeks of reading Flammarion's book, Lowell planned to observe canals on Mars during the October 1894 opposition. He knew that, on October 13, Mars would be less than 40 million miles (64.4 million km) from Earth.

In May 1894, before setting out from Boston to begin his observations, Lowell declared he would soon make a "pretty definite discovery" about intelligent life on Mars.

After a detailed search for a not-too-remote site with superb atmospheric transparency, Lowell set up an observatory overlooking the lumber town of Flagstaff, Arizona, where conditions were especially well-suited for astronomical observations. He was not disappointed in his quest for canals. In fact, he mapped more than any other observer.

In 1895, Lowell published *Mars*, the first of his three books on canals and Martians. He made much of the canal network's planet-girdling geometry, writing that "[a] mind of no mean order would seem to have presided over the system we see." Lowell believed Mars was a dying world. The ancient Martians, he claimed, had built the canal network to stave off the encroaching red desert.



▲CHRISTIAAN HUYGENS discovered the first surface feature on Mars, Syrtis Major. These sketches by Italian astronomer Giacomo Filippo Maraldi, published in 1720, comprise an early printed record of identified martian surface features. Syrtis Major is the triangular patch at the bottom right. LINDA HALL LIBRARY OF SCIENCE, ENGINEERING, AND TECHNOLOGY

Lowellian Mars quickly became an inspiration for science-fiction authors. H. G. Wells rode the wave of canal mania with his 1898 novel *The War of the Worlds* (which appeared as a motion picture in 1953 and was remade in 2005). Starting in 1912, Edgar Rice Burroughs peopled Mars with six-armed green warriors and ravishing princesses in books such as *The Gods of Mars*, *Synthetic Men of Mars*, and *Thuvia, Maid of Mars*.

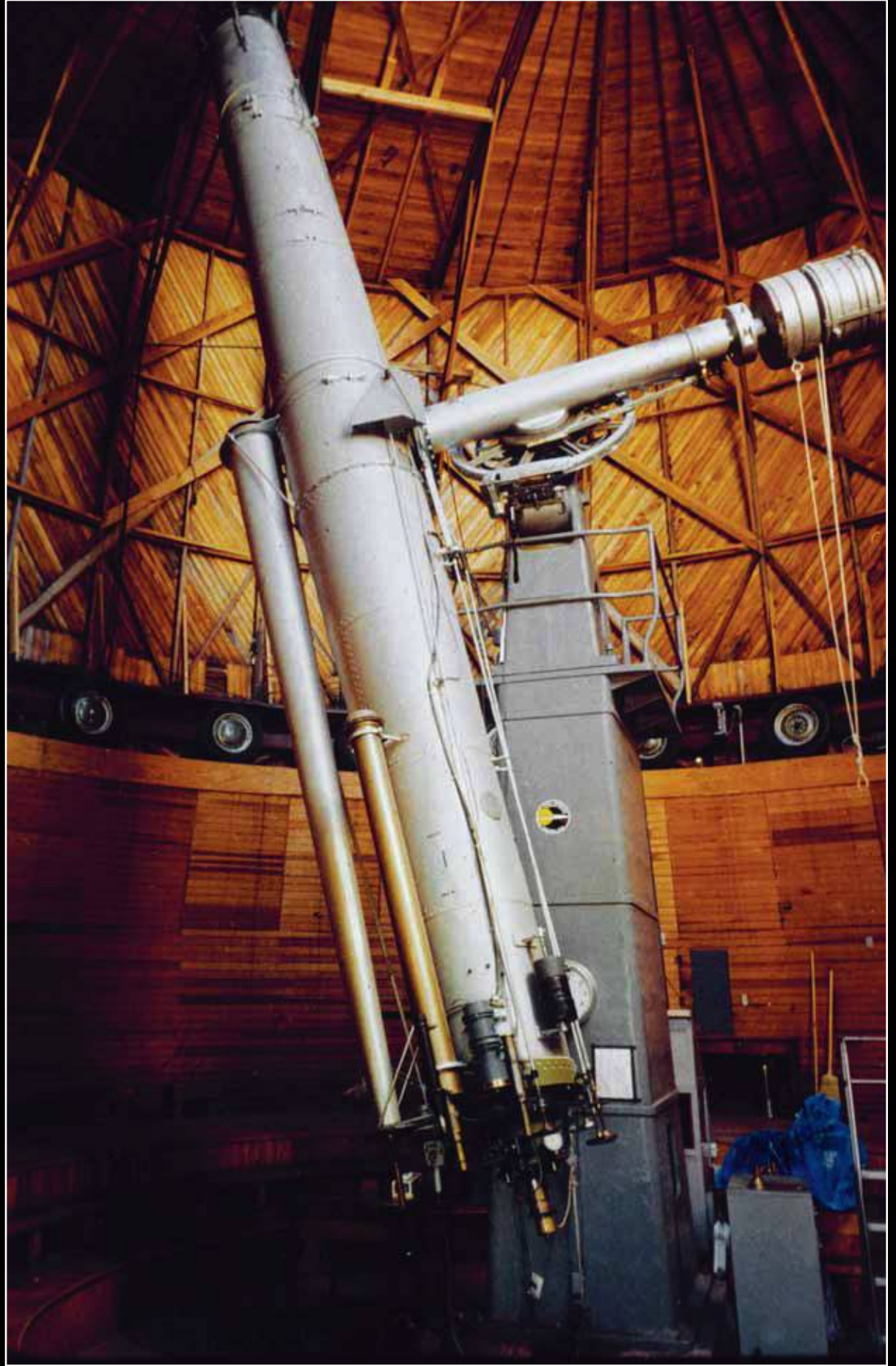
The public enjoyed Lowell's vision, but professional astronomers were horrified. To them, Lowell's outlandish theories not only endangered the reputation of their science, but also competed for funding with research on stars and galaxies, which, by the turn of the 20th century, had replaced the Moon and planets as astronomers' chief targets. Some were probably envious of the independence that wealth afforded Lowell. They worked to rein in the maverick Bostonian.

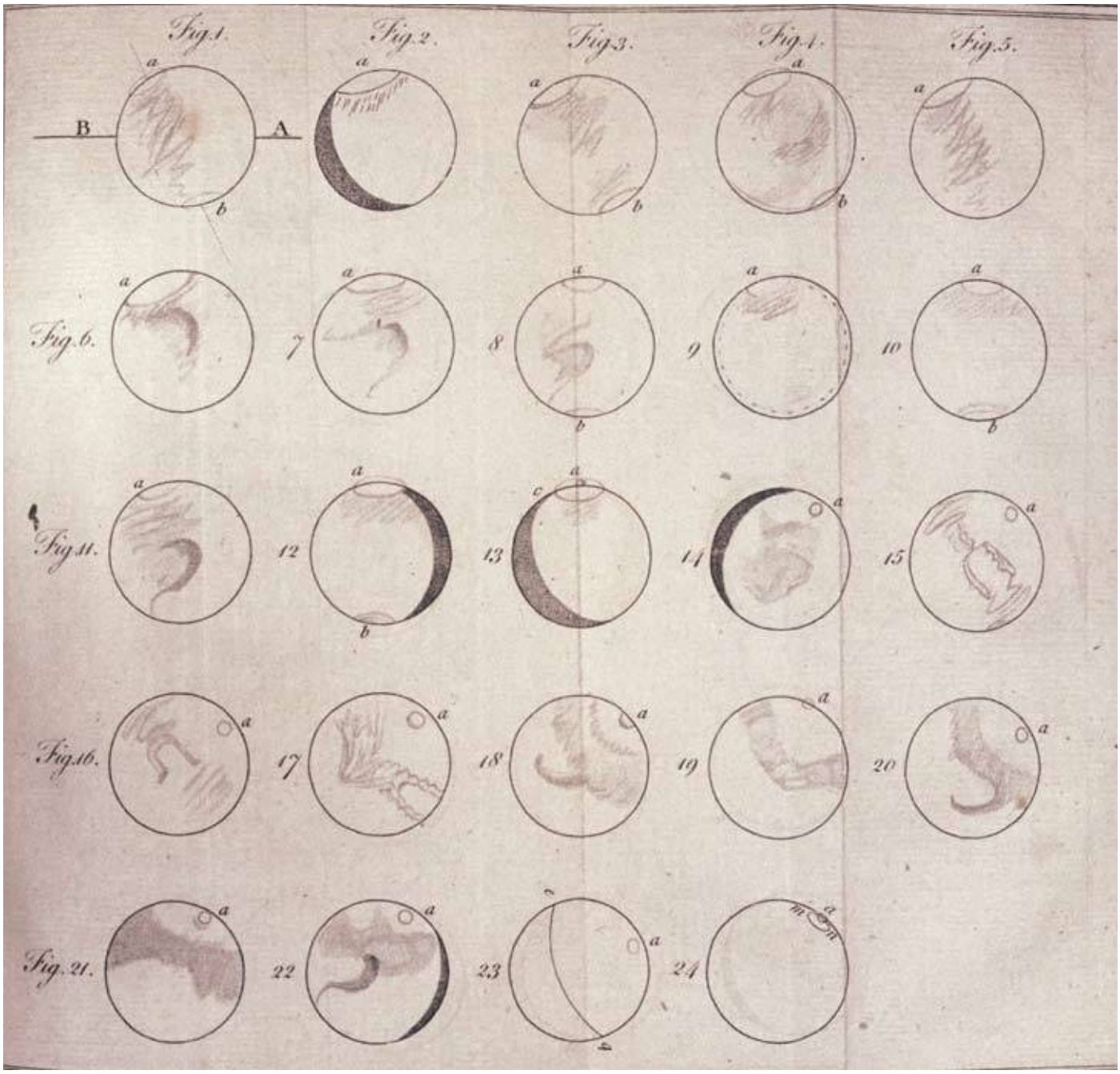
The canal craze largely ended with the perihelic opposition of 1909. Lowell and his staff on Mars Hill in Flagstaff mapped more canals. But other observers, combining dispassionate eyes with new telescopes larger than Lowell's 24-inch refractor, saw a bewildering mass of mottled detail.

Eugène Antoniadi had charted canals in 1894 using small telescopes. In September 1909, he studied Mars with the 33-inch refractor at Meudon Observatory in Paris. He wrote: "The first glance cast at the planet ... was a revelation. [It] appeared covered with a vast and incredible amount of detail ... from which geometry was conspicuous by its absence."

Canals — which Antoniadi dubbed "hideous lines" — replaced natural-appearing spots and streaks only when Earth's atmosphere grew turbulent and distorted the view. The eye and mind then imposed linear patterns on barely perceived details. Antoniadi reported his results by letter to Percival Lowell, who remained unmoved. From his Flagstaff hilltop, Lowell continued to map canals on Mars until his death in 1916.

The 20th century's first perihelic opposition ended serious discussion of intelligent life on Mars, but Lowell's influence remained profound. Observers continued to chart canals into the 1960s. Some believed they were natural fissures acting as refuges for hardy martian vegetation. In fact, most of the astronomers who still paid attention to Mars after the 1924 perihelic opposition





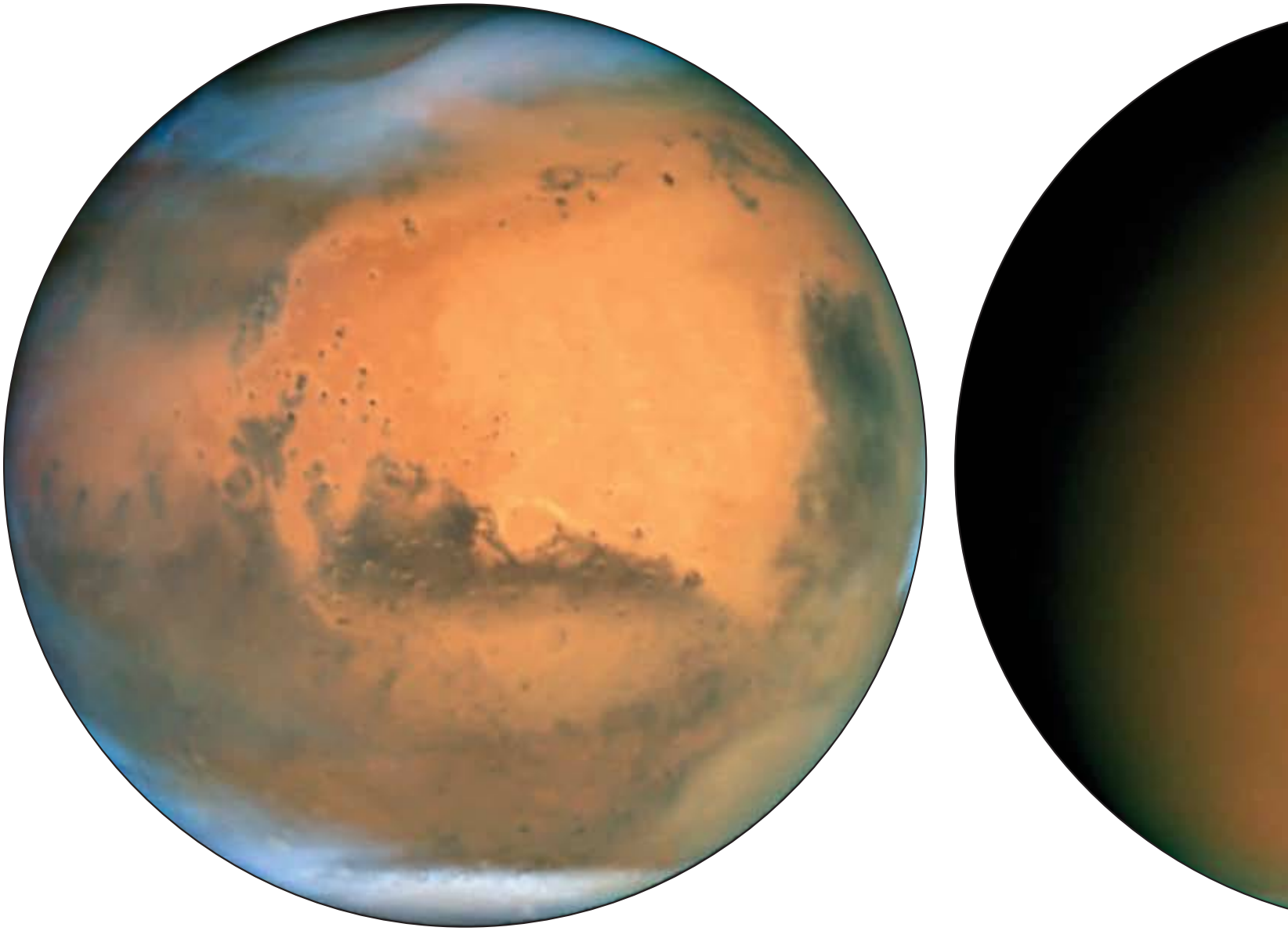
◀THE GREAT REFRACTOR at Lowell Observatory in Flagstaff, Arizona, was the instrument Percival Lowell used to build a case for intelligent life on Mars. Lowell paid the firm of Alvan Clark & Sons $20,000 for the telescope, which was installed in 1896. The 24-inch lens sits atop a 2-ton, 32-foot-long tube. During public nights throughout the year, visitors to Lowell Observatory still use the 24-inch to view Mars and other celestial wonders. LOWELL OBSERVATORY

▲ENGLISH ASTRONOMER William Herschel, who discovered Uranus in 1781, spent a lot of time observing and sketching Mars. This series of sketches he made in 1784 shows martian seasonal changes — surface markings many 18th- and 19th-century astronomers mistook for vast areas of vegetation. LINDA HALL LIBRARY OF SCIENCE, ENGINEERING, AND TECHNOLOGY

believed the dark areas, which faded in the martian autumn and darkened in the spring, were fields of vegetation.

Not until 1956 did an alternate theory receive consideration. That year, Dutch-American astronomer Gerard Kuiper — who some historians call the first planetary scientist — observed planet-wide dust storms on Mars. He hypothesized that visible changes occurred when seasonal winds blew light-colored dust over barren deserts of dark rock.

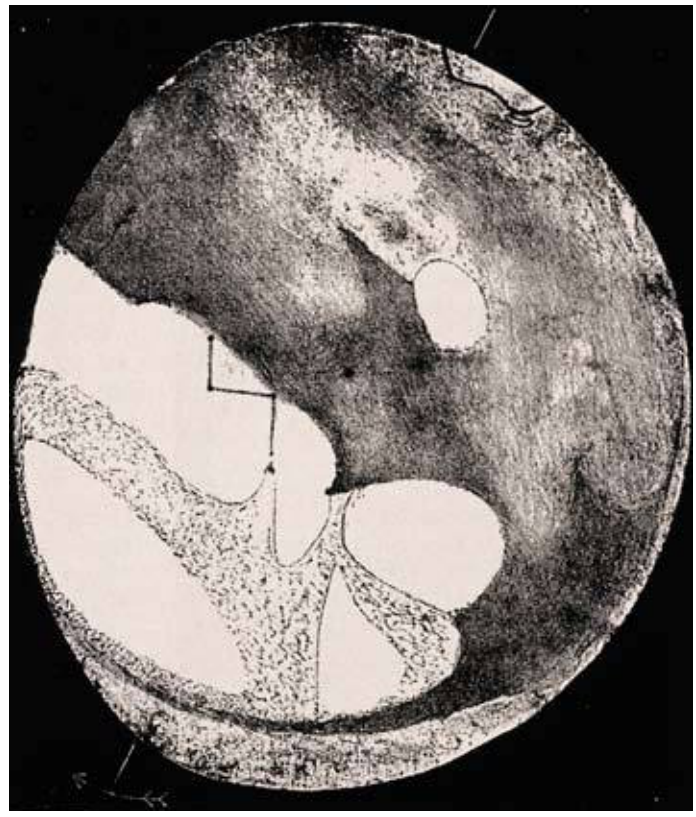
At the same time, however, new telescopic observations kept alive the notion that Mars is a living world of plants and water. In



1959, Lowell Observatory astronomer William Sinton gathered what he interpreted initially to be spectroscopic evidence of martian plants. He soon changed his mind. But then, in 1963, French astronomer Audoin Dollfus reported detecting water vapor in the martian atmosphere.

Artists, authors, and filmmakers promoted an earthlike Mars through 1964, the year NASA launched the Mariner 4 spacecraft toward Mars. The classic 1964 science-fiction film *Robinson Crusoe on Mars*, for example, gives the planet canals, edible vegetation, and a thin, almost breathable, atmosphere.

Mariner 4 shattered expectations by revealing none of these things as it flew past Mars in July 1965. Mars had craters, not canals, and its unbreathable carbon dioxide atmosphere was less than 1 percent as dense as Earth's. The impact of Mariner 4's 21



▲ **NOT ALL REPRESENTATIONS of Mars were fanciful sketches showing the canals of a dying civilization. As the 19th century ended, astronomers such as American David Peck Todd were producing realistic drawings of actual martian surface features.** MICHAEL E. BAKICH COLLECTION

◀ **BELIEF in martian life received a serious setback in July 1964, when Mariner 4 sent back 21 fuzzy images of a cratered, dead world. This image — frame 11E — shows the 100-mile-wide crater Mariner, which was named for the spacecraft.** JPL

grainy, black-and-white images is difficult to overstate. Put simply, Mariner 4 vaporized Lowellian Mars.

Surprise gave way to disappointment, nearly aborting NASA's plans for further Mars exploration. The planet seemed dead and unchanging. What was left to find? It was pointed out that better instruments would reveal more. So a growing number of planetary scientists rallied to the Red Planet's defense.

Despite the letdown, spacecraft exploration continues, producing a flood of new data. And — as the other stories in this issue reveal — the truth about Mars is every bit as fascinating as last century's fiction.

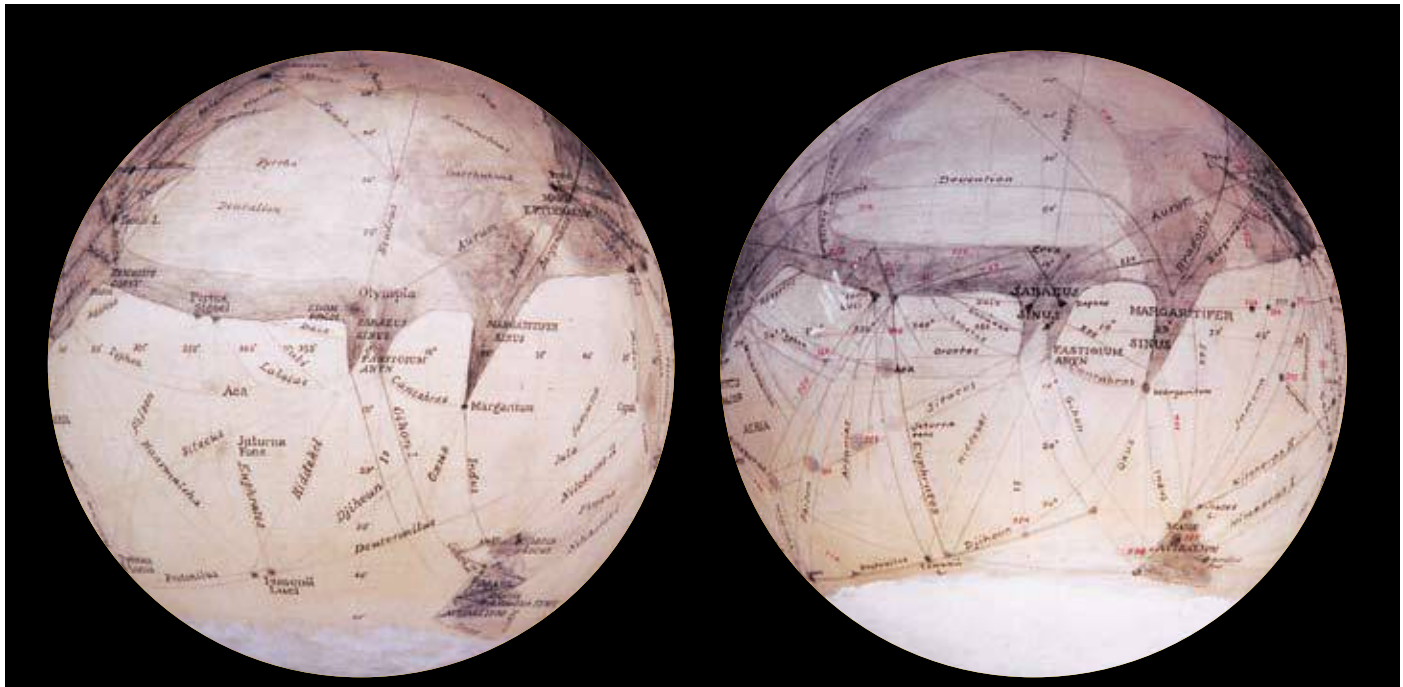
David S. F. Portree *is a Flagstaff, Arizona-based freelance writer and historian. One of his areas of interest is the martian canal controversy.*

Mars Atta

For 150 years, the Red Planet has ...

What a difference a century makes.

cks!



HAND-PAINTED MARTIAN GLOBES reveal Percival Lowell's interpretations of the Red Planet's surface. The apparent geometric layout of the "canals" led Lowell to surmise they were the work of intelligent beings. LOWELL OBSERVATORY ARCHIVES/COLEMAN-KENNEDY COLLECTION

Planet, the same question of life on Mars persists. And so far, no Martians have resisted the invasions from Earth.

Any doubts that Mars' canals were both real *and* artificial were brushed aside in 19th-century popular imagination. Only a race far superior to our own could have the technology to build a planet-girdling net of waterworks large enough to be "seen" across interplanetary space.

In the May 26, 1894, *Boston Commonwealth*, Percival Lowell — the most outspoken supporter of the canal theory — was quoted as saying: "The most self-evident explanation from the markings themselves is probably the true one; namely, that in them we are looking upon the result of the work of some sort of intelligent beings."

Early martian tales, such as Percy Greg's *Across the Zodiac: The Story of a Wrecked Record* (1880) and L. Edgar Welch's *Politics and Life in Mars: A Story of a Neighboring Planet* (1883), tell of utopian societies where a level of social cooperation sought by 19th-century European society had come to full bloom across Mars' red deserts. Not surprisingly, these stories beckoned to idealists, both those scraping out social experiments in communes and their bourgeois supporters.

Not everyone was so idealistic. Now that an advanced civilization on Mars had become a given, hard-nose realists wondered if the as-yet-unheard-from Martians were more conniving than complacent.

By the end of the 19th century, the public became increasingly aware that travel between Earth and the other planets was possible, even if far beyond any technology then available. So when H. G. Wells published *The War of the Worlds* (1898), readers believed super-advanced Martians could have the means to take over Earth.

PERCIVAL LOWELL (1855–1916) insisted Mars was a dying planet whose inhabitants dug irrigation canals to distribute a diminishing water supply to their farms and cities. LOWELL OBSERVATORY ARCHIVE

In Wells' classic novel, Europeans — who had so smugly conquered other parts of our planet — were reduced to sniveling cowards, stripped of their pompous veneer of "civilization" when faced with certain destruction by the seemingly omnipotent Martians. Wells, trained in the biological sciences, exercised sublime irony in saving the humbled humans by exterminating the invaders with the lowest forms of earthly life. *The War of the Worlds* remains one of the best works of science fiction, able to frighten American audiences in Orson Welles' famous 1938 radio adaptation (see "A century of *The War of the Worlds*" on page 35).

H. G. Wells' novel precipitated a torrent of like-minded tales that began to shape pop culture's image of Mars. Marching

(continued on page 38)

A CENTURY OF *THE WAR OF THE WORLDS*

In 1938, shortly before Halloween, Orson Welles and his program, *Mercury Theater on the Air*, became nationally — and historically — famous with a CBS Radio broadcast.

With the help of writer Howard Koch, *Mercury Theater* presented H. G. Wells' story of Martian invasions as a series of updated bulletins. The result was so realistic, many listeners believed the broadcast and were swept into a panic. The next day, Welles and his troupe were front-page news.

H. G. Wells' classic has been recreated numerous times in different formats. In 1953, *The War of the Worlds* was made into a movie, starring Gene Berry and Ann Robinson. The latest interpretation, directed by Steven Spielberg, stars Tom Cruise. Meanwhile, the book itself has been translated into many languages throughout its 108-year life. — *Jeremy McGovern*

H.G. WELLS'
THE WAR OF THE WORLDS
Color by Technicolor
A MIGHTY PANORAMA OF EARTH-SHAKING FURY!
TWO YEARS IN THE MAKING!
NOTHING SO SPECTACULAR EVER PUT ON FILM BEFORE!
PRODUCED BY GEORGE PAL
WHO GAVE YOU DESTINATION MOON AND WHEN WORLDS COLLIDE
THE WAR OF THE WORLDS

PARAMOUNT/THE KOBAL COLLECTION

"At most terrestrial men fancied there might be other men upon Mars, perhaps inferior to themselves and ready to welcome a missionary enterprise. Yet across the gulf of space, minds that are to our minds as ours are to those of the beasts that perish, intellects vast and cool and unsympathetic, regarded this earth with envious eyes, and slowly and surely drew their plans against us. And early in the twentieth century came the great disillusionment." *H. G. Wells,* The War of the Worlds *(1898)*

▲ *ABBOTT & COSTELLO GO TO MARS* (1952). Mars looked eerily like Mardi Gras in this film adventure. After Abbott and Costello accidentally launch a Mars-bound rocket — which ends up landing in the "alien" world of New Orleans — they blast off for Venus only to find a civilization of women. The comedy duo's interplanetary escapades played off of their audience's belief that such travel indeed was possible. UNIVERSAL/THE KOBAL COLLECTION

▲ *INVADERS FROM MARS* (1953). Released at the height of the Red Scare, *Invaders from Mars* struck at the American fear of a covert, conniving menace. Martian aggressors take the place of communists in this sci-fi classic. The nightmare begins when a young boy, David, sees a flying saucer land. As adults are brainwashed and controlled by the invaders, David enlists help from his school's nurse to confront the threat. 20TH CENTURY FOX/THE KOBAL COLLECTION

▲ *ROBINSON CRUSOE ON MARS* (1964). Before Mariner 4 blasted off for the first martian flyby in 1964, Hollywood released this retelling of Daniel Defoe's famous story. Astronaut Kit Draper (Paul Mantee) finds himself stranded on the Red Planet, where he must contend with a hostile environment, loneliness, and, eventually, alien slave-masters. Elements of this space adventure found their way into *Enemy Mine* (1985), *Total Recall* (1990), and *Stargate* (1994).

PARAMOUNT/THE KOBAL COLLECTION

▲ *MARS ATTACKS* (1996). Director Tim Burton used an all-star cast — including Jack Nicholson, Glenn Close, and Pierce Brosnan — in his over-the-top homage to 1950s' science-fiction cinema. With bulb-headed aliens zapping every human in sight with ray guns, this film spoofs its predecessors while poking fun at politics, celebrities, and American institutions. The wackiness climaxes with the Martians defeated and Tom Jones crooning his hit "It's not unusual."

WARNER BROS./THE KOBAL COLLECTION/INDUSTRIAL LIGHT & MAGIC

(continued from page 34)
in lockstep with the Martian warriors was the proselytization by Percival Lowell.

An accomplished mathematician, diplomat, and avid follower of oriental customs earlier in life, Lowell preached of a benign and utopian Martian civilization. On Lowell's Mars, Darwinian forces dictated day-to-day existence. Irrigation canals were built because Mars is a dying world, Lowell maintained.

Planetary science of the day held that Mars was older than Earth, much further along the path to decrepitude. Lowell's Mars once had oceans but, over the eons, they dried up, leaving a desperate, brave, hyper-intelligent race to maximize dwindling resources.

Naysayers, such as evolution's codiscoverer, Alfred Russel Wallace (1823–1913), proclaimed Mars dead as a doornail. But they had little effect in breaking Lowell's spell. Lowell's books — *Mars* (1895), *Mars and Its Canals* (1906), *Mars As the Abode of Life* (1908), and *The Evolution of Worlds* (1909) — explicitly compare the conditions on Mars to what he foresaw as the beginning of the end for life on Earth: the inexorable loss of our precious fluid, which, in some distant future, would leave our planet a vast desert.

WALT DISNEY MEETS WITH Wernher von Braun (right), then chief of the Guided Missile Development Operation Division at the U.S. Army Ballistic Missile Agency. In the 1950s, von Braun worked with the Disney Studio as a technical advisor, helping make three films about space exploration for television: Man in Space (1955), Man and the Moon (1955), and Mars and Beyond (1957).

NACA/NASA, COURTESY RMP PHOTO ARCHIVE

With Lowell's death in 1916, the idea that Mars was populated with sophisticated beings lost its champion, yet his vivid portrait of life and earthlike conditions on Mars framed the discussion of the Red Planet that persists today.

Lowell's inhospitable martian deserts were the settings for early 20th-century sword and sorcery fantasies. The best known are those of Edgar Rice Burroughs — the author of the *Tarzan* series — whose martian civilization was dying from thirst.

Burroughs' hero, John Carter, a Civil War veteran, escapes to Mars from a cave where he was hiding from Apache Indians. Barsoom, as Mars is known by the natives, is a dangerous and exciting place, where characters are either superheroic or felled by their human weaknesses in a style that would make George Lucas proud.

Generations of kids were enthralled by Burroughs' books. In *Cosmos*, Carl Sagan proclaimed that Burroughs motivated his own first steps toward a lifelong romance with Mars: "I can remember spending many an hour in my boyhood, arms resolutely outstretched in an empty field, imploring what I believed to be Mars to transport me there."

The global struggle against Nazism, the rise of Communism, the relentless march of technology, and the threat of nuclear annihilation led to the last flush for Mars as a place of unconstrained fables. German V-2 rockets explosively announced the arrival of a technology that could be developed for space travel. The V-2's chief engineer, Wernher von Braun — regarded as the "father" of the U.S. space program — seized control of the serious public discussion in the early 1950s.

Von Braun portrayed the use of rockets to explore Mars in a series of articles, books, films, and public appearances — he even collaborated with Walt Disney on three educational films. Given these influences, early 1950s B-grade science-fiction movies typically had attractive couples travel to Mars in a rocket ship to find the remnants of a Martian civilization that had destroyed itself in a nuclear war. Such, for instance, is the plot of the film *Rocketship X-M* (1950).

Around the same time, the classic George Pal film version of *The War of the Worlds* (1953) made the scene. Pal's interpretation reminded audiences that flying saucers, another post-war rage, could and often did substitute for rockets.

Films such as *Invaders from Mars* (1953), *I Married a Monster from Outer Space* (1958), and *Invasion of the Body Snatchers* (1956) capitalized on the public's fear of invasion brought on by the Great Red Scare. Warner Brothers' Marvin the Martian animated cartoons often preceded these screenings.

Snuggled among these drive-in movies was the last breath of Mars, not as revealed by science, but as a faraway land of fantasy and adventure. Ray Bradbury's novel *The Martian Chronicles* (1950), which many critics argue transcends the boundary between pulp science fiction and mainstream literature, portrays this mystical Mars beautifully.

The arrival of the Space Age and the first robotic missions to Mars broke asunder pop culture's fantastic ideas of Mars. Mars

David Bowie, "Space Oddity" (1969)

This is Major Tom to ground control
I'm stepping through the door And
I'm floating in a most peculiar way
And the stars look very different
today

For here Am I sitting in a tin can Far
above the world Planet Earth is
blue And there's nothing I can do

Though I'm past one hundred thou-
sand miles I'm feeling very still And
I think my spaceship knows which
way to go Tell my wife I love her
very much she knows

Ground control to Major Tom Your
circuit's dead, there's something
wrong Can you hear me, Major
Tom? Can you hear me, Major Tom?
Can you hear me, Major Tom? Can
you..."

developed a split personality. Some simply ignored the messages from our probes and continued to release such comical works as the TV sitcom *My Favorite Martian* (1963–66).

The cultural revolution of the 1960s nourished more fanciful, surreal, yet socially critical — and even downright paranoid — books, such as Phillip K. Dick's *Martian Time Slip* (1962) and *The Three Stigmata of Palmer Eldritch* (1965).

At that time, even the music scene capitalized on Mars in David Bowie's "Space Oddity" (1969), his LP *The Rise and Fall of Ziggy Stardust and the Spiders from Mars* (1972), Elton John's "Rocket Man" (1972), and the Grateful Dead's album *From the Mars Hotel* (1974).

Yet through the haze, the march of scientific discovery created an alternative "realistic" Mars. Even as early as the 1950s, writers told stories of bold adventure in Mars-as-revealed-by-science settings. For example, Arthur C. Clarke's *Sands of Mars* (1951), along with Isaac Asimov's *The Martian Way* (1955), contained the first serious proposals to make Mars more earthlike by a planetary engineering process called terraforming.

Since then — and especially after the successful Viking and Mariner missions of the 1970s revealed dried up, but water-carved, channel networks and Arizona-size volcanoes — some novels, films, and television shows have followed Clarke and Asimov's lead. For example, three novels by Kim Stanley Robinson, *Red Mars* (1992), *Green Mars* (1993), and *Blue Mars* (1996), portray a realistic Mars as a backdrop for thoughtful social and ecological commentary.

Now, both sides are going strong and even cross-pollinating. A post-psychedelic non-utopian movement in science fiction sometimes referred to as "cyperpunk" mixes and matches various martian realities. If this genre has a founder, it might be Phillip K. Dick.

Several films are mutations of Dick novels and short stories ranging from the superlative *Blade Runner* (1982) to the lackluster *Total Recall* (1990).

The final addition to pop Mars is real Mars — championed by the late, great Carl Sagan. Starting in the 1960s, Sagan brought Mars to the public with eye-catching pieces in magazines like *National Geographic* and *Parade*, then into America's bedrooms with his telegenic appearances on *The Tonight Show with Johnny Carson*. Sagan's PBS series *Cosmos* (1980) remains one of PBS's most-watched programs.

NASA's public relations program also has evolved. Apollo Moon-mission footage was produced by the company that made U.S. Army venereal-disease-avoidance-training videos. Now, the public is engaged in the latest Mars exploration and other space missions through a variety of media outlets with competent, media-savvy packaging and programming.

Today's Mars can still be a place of fantasy, a screen upon which we project our visions or nightmares, as well as a place whose actual vistas are increasingly well known — a place awaiting our inevitable arrival.

A POP-CULTURE-SAVVY NASA now routinely incorporates icons such as Warner Brothers cartoon characters Marvin the Martian and Daffy Duck (in his guise as Duck Dodgers in the 24½th century) into mission patches. Here, they grace the patches of the ongoing Mars Exploration Rover Program. WARNER BROS. CONSUMER PRODUCTS

Jeff Moore *is a planetary geologist at NASA's Ames Research Center. His research has focused on a range of topics relating to the geologic evolution of planetary landscapes and surface materials.*

First visitors from EARTH

Early flybys implied the Red Planet's nickname should be Dead Planet instead, but the first orbiters changed our view of Mars again

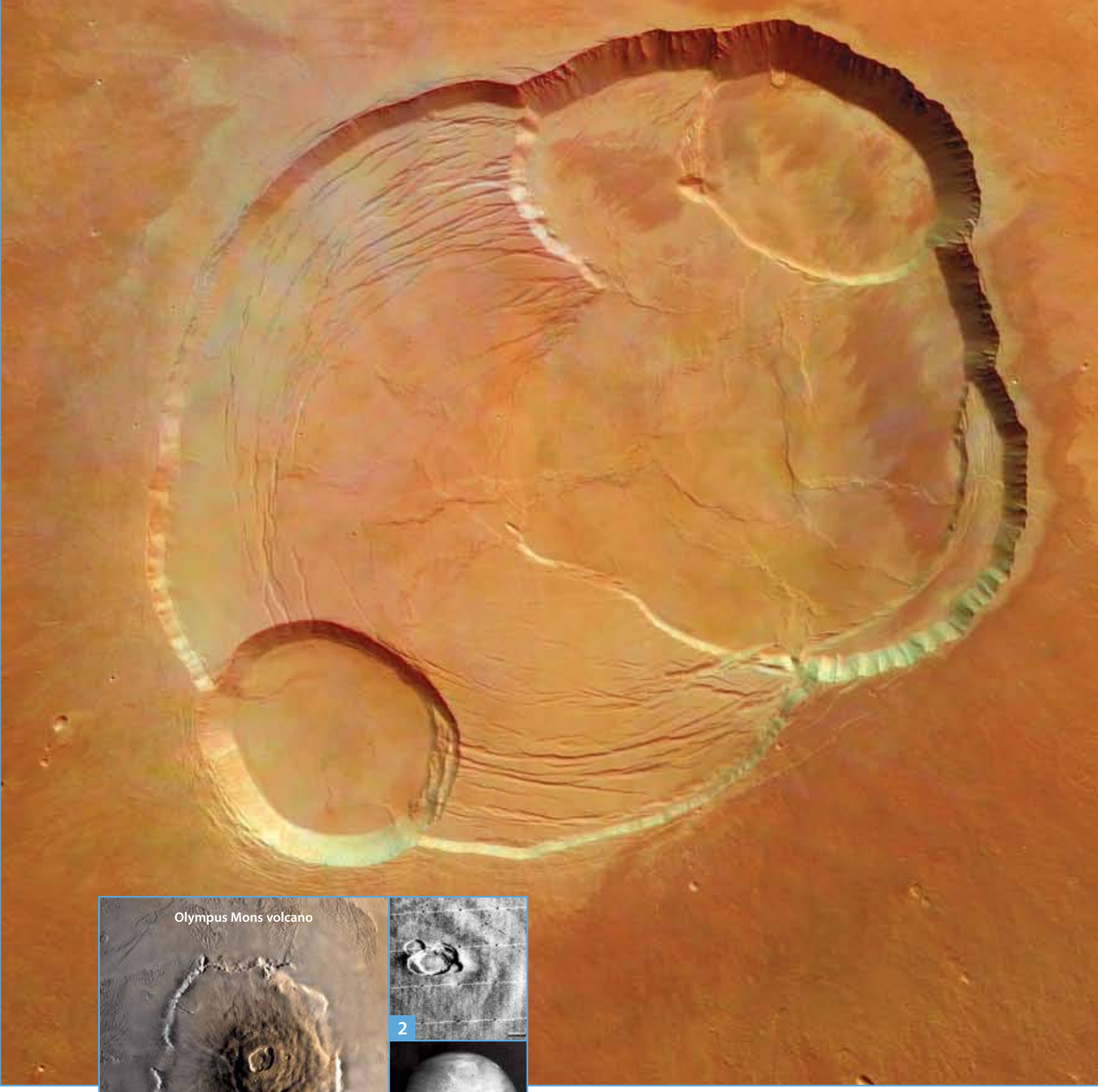
BY MARK NORMAN

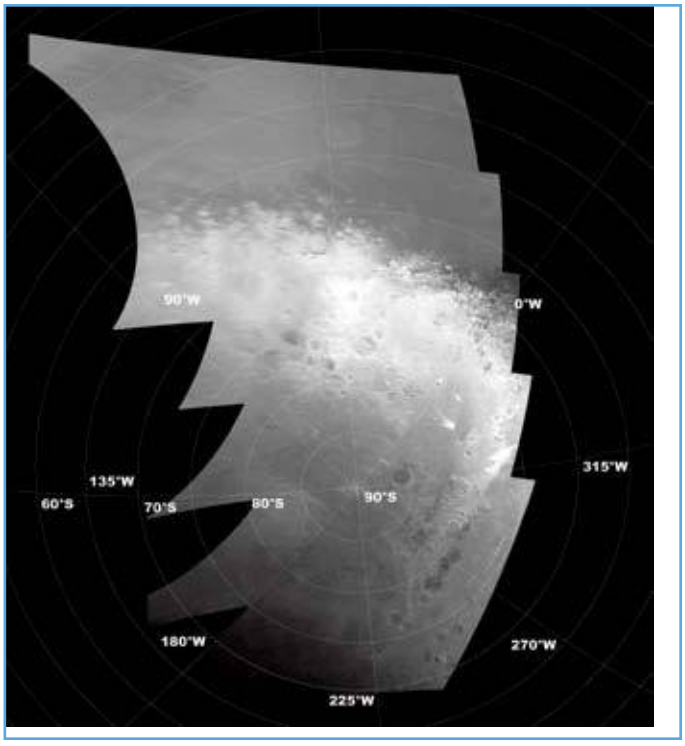
1965 was a watershed year

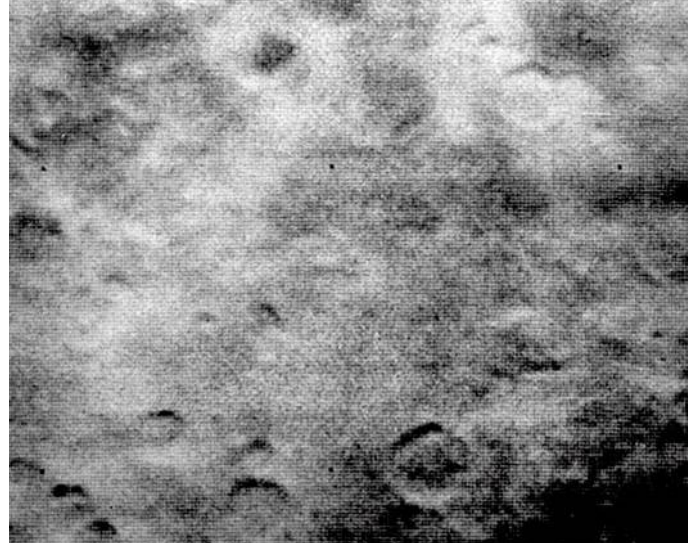
1

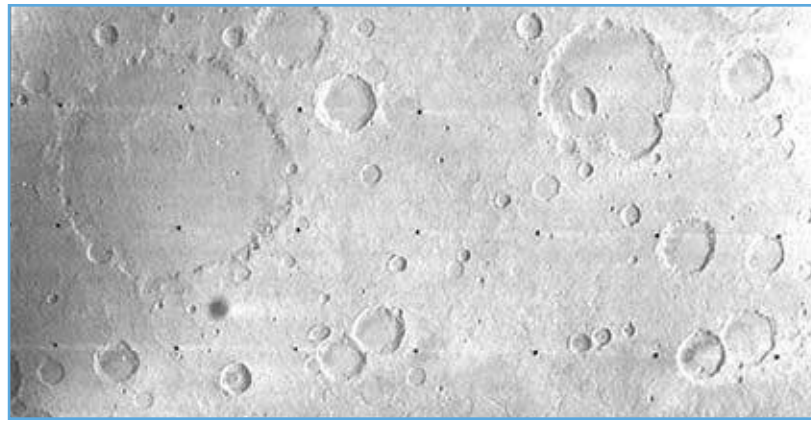
2

3


Olympus Mons volcano
1
2
3







the solar panels. Engineers had enough time to analyze the problem and fix Mariner 4 to ensure it would not suffer the same fate. On November 28, NASA successfully launched the second spacecraft toward Mars, and a few days later, the Soviets launched Zond 2. The race to Mars was on.

The Soviets lost contact with Zond 2 in spring 1965, so Mariner 4 was on its own. NASA mission controllers resolved a few early, minor problems with the onboard navigation system, and the spacecraft performed admirably as it passed within 6,000 miles (10,000 kilometers) of Mars July 14, 1965.

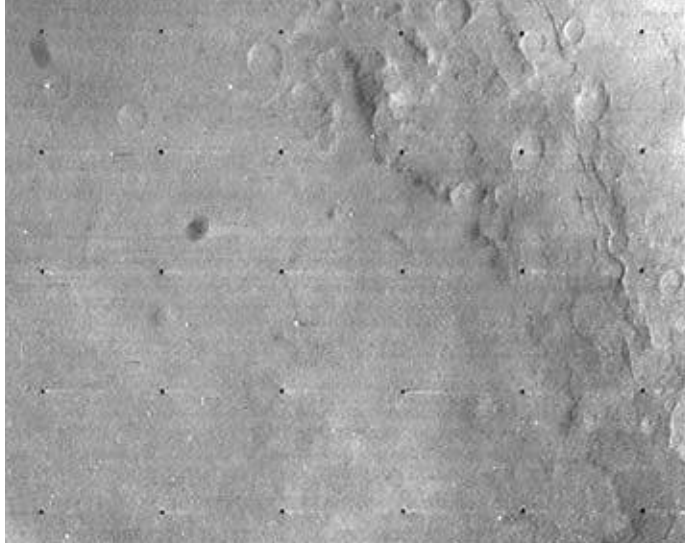
Mariner 4 took 21 images of Mars, covering about 1 percent of the planet's surface in the southern highlands. Each image from the spacecraft's vidicon camera captured 200 x 200 pixels (0.04 megapixel) in 64 shades of gray. (For comparison, an inexpensive, 5-megapixel digital camera today has about 100 times better resolution.) Mariner 4 recorded the images on tape and beamed them to Earth after the flyby. The 10-watt transmitter operated at a rate of 8.3 bits per second, so it took 8 hours and 20 minutes to transmit a single picture.

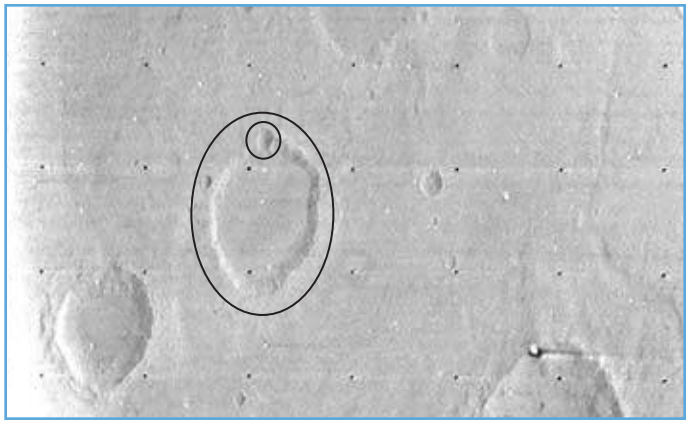
Mission scientists and the public alike were held in suspense as each image slowly made its way home. But it soon became apparent that Mars was much more similar to the Moon than to Earth. The real Mars showed a heavily cratered surface with no evidence of canals, rivers, or water of any kind. The martian atmosphere has a density only 1 percent that of Earth's. And the planet has no magnetic field, evidence that it no longer has a liquid core.

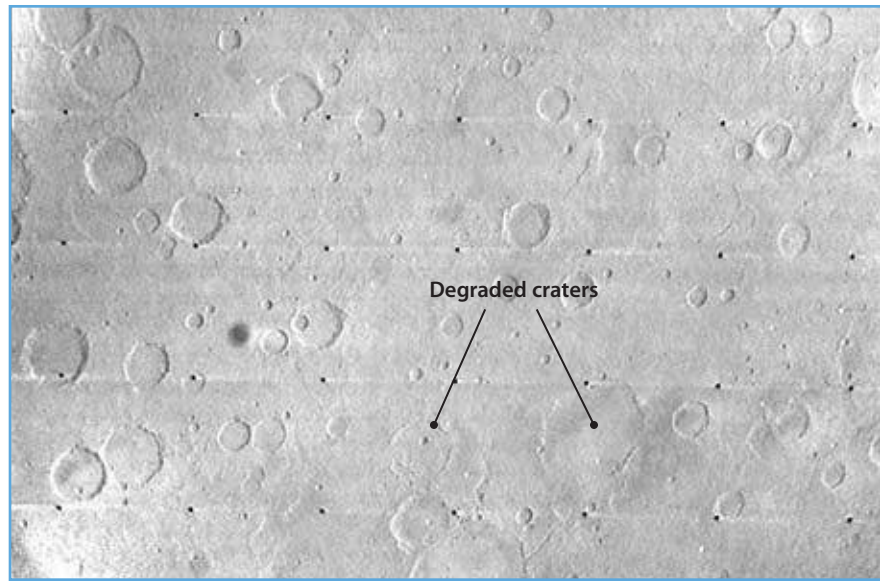
The press and many scientists painted the Mariner 4 pictures as a disappointment, at least in terms of the possibility that life existed on Mars. A front-page story in the July 30 *The New York Times* stated: "A heavy, perhaps fatal, blow was delivered today to the possibility that there is or once was life on Mars. The Mariner 4 photographs taken of the planet at close range July 14 show a crater-pocked landscape lacking any sign that there has been water erosion there. There is no evidence of river valleys or ocean basins."

Yet not everyone shared the glum assessment of life's chances on the Red Planet. Eminent chemist Stanley Miller declared the Mariner pictures revealed "absolutely nothing" regarding the question of life on Mars.

Mariners 4, 6, and 7







The Moon-like Mars revealed by Mariner 4 did not dampen NASA's enthusiasm for martian exploration. Did these pictures, which covered only 1 percent of the surface, truly represent Mars? What would explorers from another planet think of Earth if they saw 20 low-resolution images of the Sahara Desert?

NASA prepared two improved Mariner spacecraft for launch in 1969. Mariners 6 and 7 would take pictures covering 20 percent of the planet with a resolution 10 times higher than Mariner 4. Each spacecraft carried both wide-angle and narrow-angle cameras designed to take moderate- and high-resolution pictures of the same areas. The two spacecraft also carried spectrometers to analyze the martian atmosphere, surface temperatures, and the rocks and minerals composing the crust.

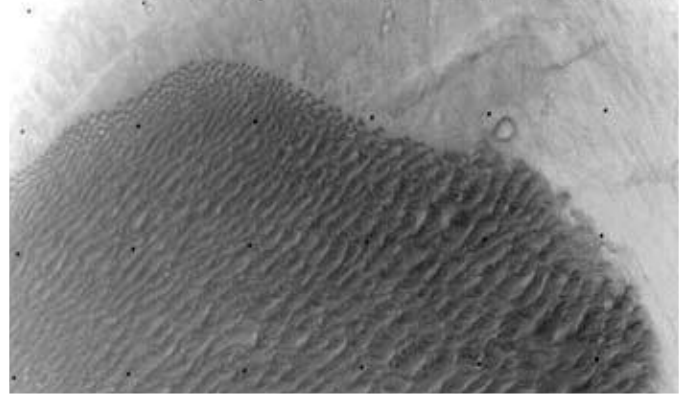
Both Mariners 6 and 7 were launched toward Mars in early 1969 (February 24 and March 27, respectively). The Soviets launched a Mars-bound spacecraft in the same period, but it failed early. With the recent successes of the United States' manned program, which included orbiting three astronauts around the Moon in Apollo 8, the U.S. space program finally was equaling or surpassing the achievements of its cold-war rival.

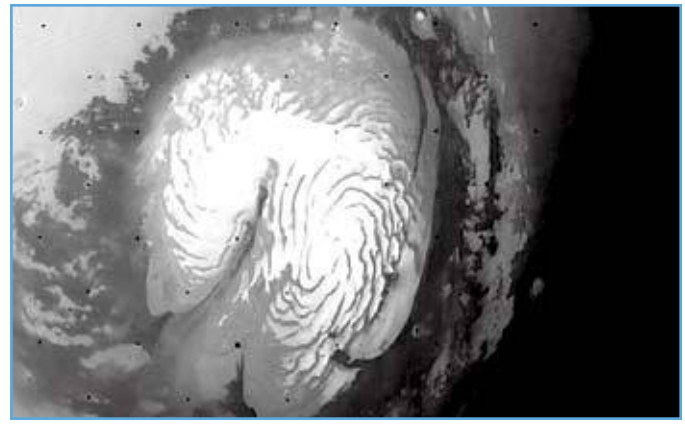
Despite several anxious moments, the Mariners returned a rich harvest of science from Mars. Mariner 6 came within 2,132 miles (3,431 km) at closest approach July 31, and Mariner 7 swooped within the same distance August 5. Combined, they sent back 57 high-resolution pictures and more than 100 lower-resolution images. And once again, Mars appeared to be a heavily cratered, Moon-like world with no signs of volcanic activity.

However, a few pictures hinted Mars might not be like the Moon in all respects. Two Mariner 6 frames showed a small valley filled with material scientists described as jumbled, broken, and blocky — a type of feature ultimately called chaotic terrain. Images also revealed degraded craters with flat floors, unlike any found on the Moon. The scientists concluded these craters had been eroded by some unknown process.

Mariners 6 and 7 detected an atmosphere containing about 90 percent carbon dioxide, less than 1 percent oxygen, and no nitrogen, the main ingredient of Earth's atmosphere. The surface

Mariner 9





pressure hovers between 5 and 10 millibars, equivalent to that outside a jet flying at 35,000 feet above Earth's surface.

Scientists were puzzled by the lack of nitrogen in the atmosphere and volcanoes or volcanic plains on the surface. Apollo 11 had just returned basaltic volcanic rock from the Moon, showing its interior once had been hot enough to melt rock. Being much larger than the Moon, Mars also should have had periods of volcanic eruptions. Such eruptions on Earth release nitrogen into the atmosphere, so scientists expected a volcanically active Mars should have nitrogen in its atmosphere, too. Had Mars always been volcanically dead? The evidence seemed to say yes. The lack of nitrogen also concerned biologists, because this element is essential for life on Earth.

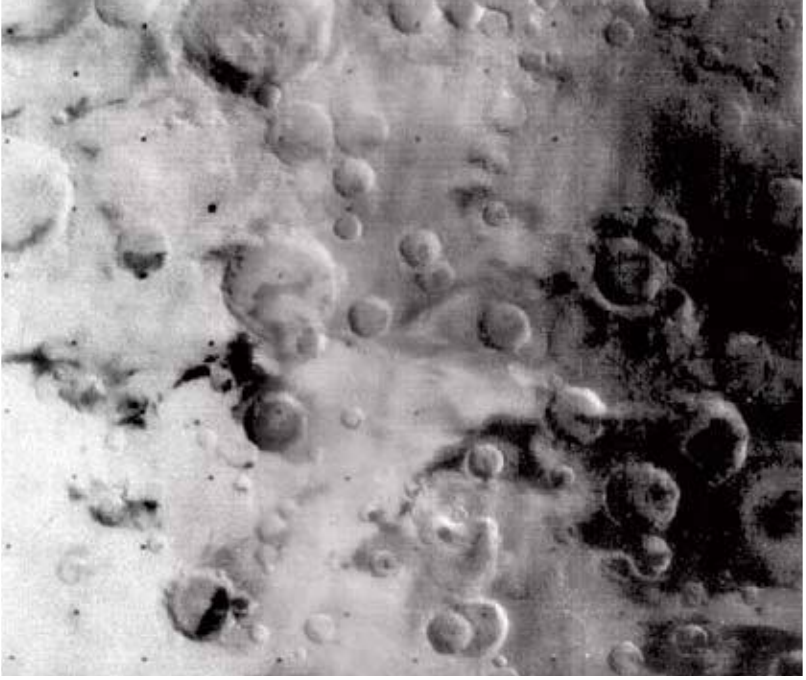
In retrospect, we know these early Mariner missions imaged the most Moon-like portions of Mars and missed the areas we now think of as martian: giant volcanoes, ancient river valleys, and the giant canyon system. To truly understand a planet requires a long-lived orbiter that can map the entire surface at moderate resolution and key areas at high resolution. That was exactly the mission planned for Mariner 9.

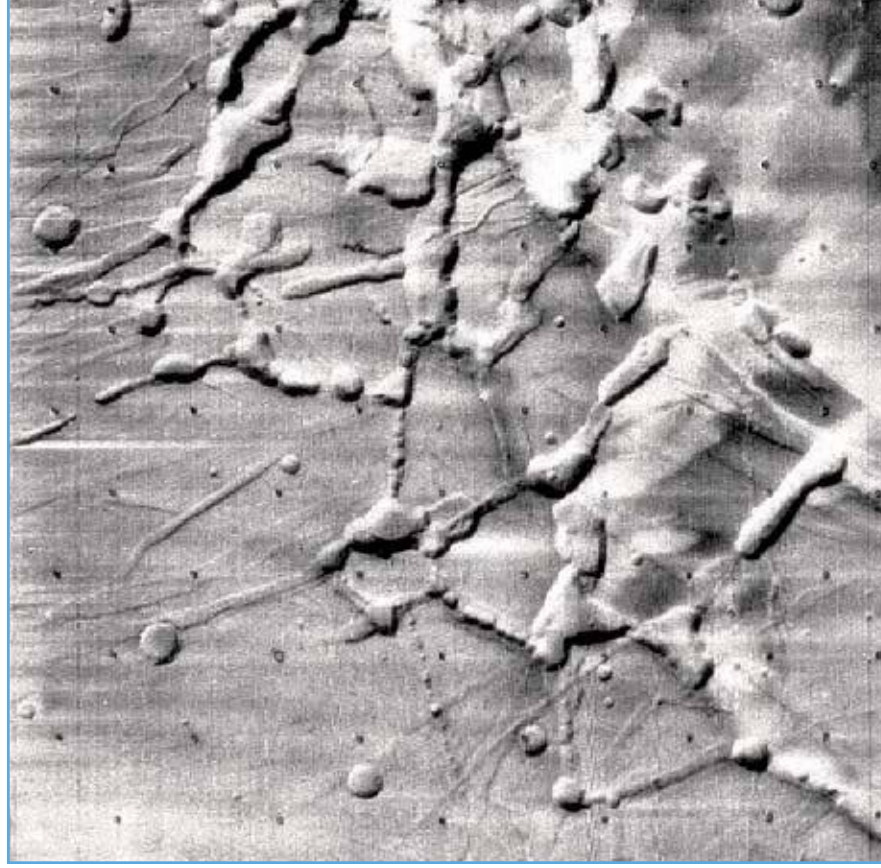
1971 looked to be a banner year for Mars exploration. Two Soviet and two American missions were launched, and each was intended to orbit Mars for an extended period. Mariner 8 ended up at the bottom of the Atlantic Ocean after its May 9 launch when the Atlas rocket's upper stage tumbled out of control. Its twin, Mariner 9, took off successfully May 30.

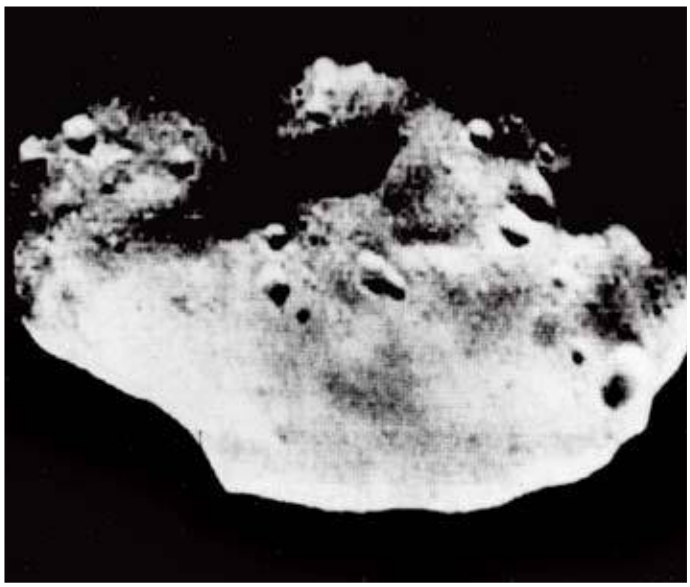
The Soviets launched their Mars probes a few days before Mariner 9. The Mars 2 and Mars 3 spacecraft were much bigger than their American counterparts, fueling speculation in the press they carried landers or even rovers. Although U.S. astronauts had beaten Soviet cosmonauts to the Moon, many still fretted about the Soviets gaining an advantage.

On November 13, 1971, Mariner 9 became the first spacecraft to orbit another planet. Much to the chagrin of mission scientists, however, a giant dust storm totally obscured Mars' surface. All the early pictures made Mars look like a planet-size cue ball. Astronomers had long known Mars sometimes suffers such global storms, which usually dissipate after several weeks.

Fortunately, NASA designed Mariner 9 to orbit Mars for months, so it could wait out the dust storm. The Soviet spacecraft couldn't. They were pre-programmed and sent back images of the dust-shrouded planet. Their missions ended before the atmosphere cleared. Adding insult to injury, both landers carried by the orbiters failed to reach the surface in working order. Of the four spacecraft launched to Mars in 1971, only Mariner 9 returned useful data.







MARS' MOON PHOBOS was nothing more than a point of light before Mariner 9 viewed it up close. The spacecraft showed this tiny, oblong world, which measures only 8 miles in its longest dimension, to be chock full of impact craters. NASA/JPL

As the dust storm slowly abated, surface features appeared in the Mariner 9 images. Planetary scientists spotted four enigmatic dark spots in some of them. By the end of December, it became apparent these fours spots were the summits of giant volcanoes. Scientists soon realized these volcanoes dwarfed any mountains found on Earth — the tallest, now known as Olympus Mons, soars more than 9 miles (15 km) above its surroundings.

As the atmosphere cleared through January, images revealed a huge system of equatorial canyons. The canyons stretch nearly a quarter of the way around Mars, a distance about that from New York to San Francisco. Scientists named this giant network Valles Marineris, after its discoverer, Mariner 9. Smaller volcanoes also appeared, along with huge dune fields and curious fracture patterns — every day seemed to bring a new discovery.

Mariner 9 also discovered water-carved valley networks, some fed by the chaotic terrain first seen by Mariners 6 and 7. Images revealed huge outflow channels circling the Chryse Planitia basin. Evidence piled up that Mars must have had significant periods when water flowed across its surface, attesting to an ancient past with drastically different climatic conditions. Mariner 9 laid to rest previous notions that Mars was a Moon-like planet.

After completing 698 orbits and taking 7,329 pictures, Mariner 9 ran out of attitude-control gas October 27, 1972, and was turned

Viking Lander

1

2

3

4

5

off. The spacecraft revealed Mars to be an infinitely complicated and unique geologic body. But it also dispelled the Lowellian vision of canals, vegetation, and intelligent life. In fact, the Mariner spacecraft turned up nary a shred of evidence that life ever existed on the Red Planet. But the question of life on Mars would not go away. The only way to answer it was to land on Mars.

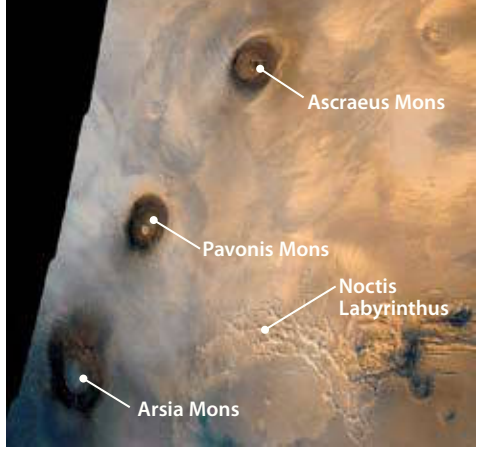
The ambitious Viking program was designed to do just that. Viking consisted of two identical orbiters carrying identical landers. The twin spacecraft lifted off August 20 and September 9, 1975, and arrived at Mars June 19 and August 7, 1976.

This time, the United States had no competition. In 1973, the Soviets had sent a pair of orbiters (Mars 4 and 5) and landers (Mars 6 and 7) to the Red Planet. Once again, the missions were plagued with problems. Of the four missions, only one orbiter returned any useful data, and only for 20 orbits. The Soviets wouldn't attempt another Mars mission for 15 years.

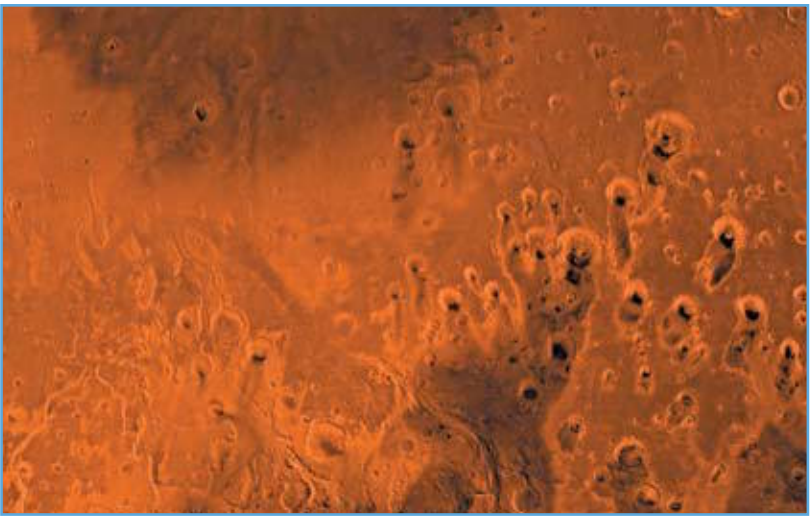
The Viking orbiters were designed to find safe spots for the landers, characterize the geology and environment of the landing sites, and further study Mars' surface and atmosphere. The main thrust for the landers was to search for life. Their panoramic cameras certainly could capture pictures of any martian critters that might stop by for a visit, but most scientists were relying on sophisticated instruments to analyze the soil and atmosphere to test for signs of life, either past or present. Mission scientists gave odds on finding life on Mars that ranged from one-in-10 to one-in-a-million.

Viking Lander 1 touched down in the Chryse Planitia basin July 20, 1976, the seventh anniversary of Apollo 11's Moon landing. Viking Lander 2 set down September 3 in Utopia Planitia, on the other side of the planet.

Once on the surface, each lander sc oped up smil and placed it into the life-sciences package, where a trio of biology experiments tested for signs of metabolism and the breakdown of organic compounds (see "Looking for life, Viking style," page 19). Only the labeled-release experiment showed a positive result — after adding a small amount of "nutrient soup," the experiment detected a rapid release of gas. Because neither lander detected any organic molecules, scientists think inorganic processes best explain the



Viking Orbiter



labeled-release experiment results. The consensus of scientists is that Viking found no evidence of life, either past or present.

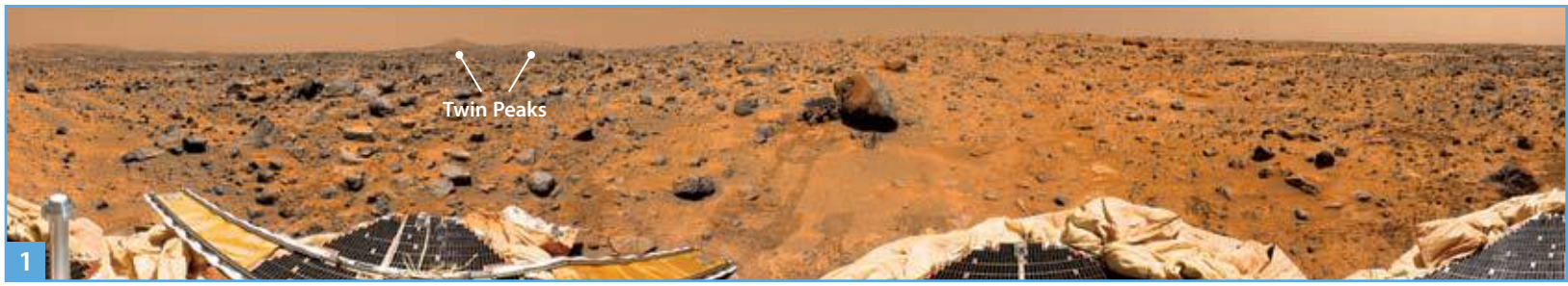
The Viking landers also analyzed their immediate surroundings. Scientists concluded the soil's chemical makeup arose through the weathering of iron- and magnesium-rich rocks, such as basalt. Mariner 9 and the Viking orbiters all returned images of volcanoes and lava flows consistent with widespread basaltic volcanism. The discovery of basalt indicated a layered planet like Earth, with a core, mantle, and crust.

The Viking orbiters went on to map Mars at resolutions as high as about 65 feet (20 meters) per pixel. During their extended missions, which lasted more than a full martian year, the two spacecraft returned more than 52,000 images, including close-up views of the martian moons Phobos and Deimos. The orbiters mapped the migration of water in the atmosphere and measured surface temperatures during both night and day. They also showed that the residual northern polar ice cap — the part remaining at the end of summer — consists of water ice, while the residual southern cap is covered in frozen carbon dioxide.

The Mariner 9 and Viking missions were successful beyond anyone's expectations. The data they returned fundamentally altered our view of Mars, and scientists continued to analyze this treasure trove for more than 20 years. The observations revealed Mars as a geologically complex planet with a past far different from its present.

Certainly, Mars was not Moon-like, nor was it earthlike. Mars was a new and foreign world, with no evidence of life. The issue of life on Mars had shifted to whether life existed at some time in the distant past and, if not, why not? Only detailed surface studies with sophisticated rovers could answer such questions.

Mars received no more visitors from Earth until 1989. The Soviet Union launched two ambitious missions toward Mars in July 1988. Their primary goal was to study the larger martian moon, Phobos. The spacecraft, Phobos 1 and 2, carried remote-sensing instruments as well as small landers designed to set down on the moon. Although Phobos 1 was lost shortly after launch, Phobos 2 entered martian orbit in January 1989. Unfortunately, it was also lost just before its rendezvous with the moon.



1

2

1

2

In September 1992, the United States launched Mars Observer, an orbiter designed to study Mars' surface and atmosphere. Eleven months later — and just a few days before reaching the planet — mission controllers lost contact with the spacecraft and never heard from it again. Nobody knows exactly what happened. The best guess is that a fuel line ruptured while a tank was being pressurized. The Russians attempted another orbiter mission in 1996, but it failed to leave Earth orbit.

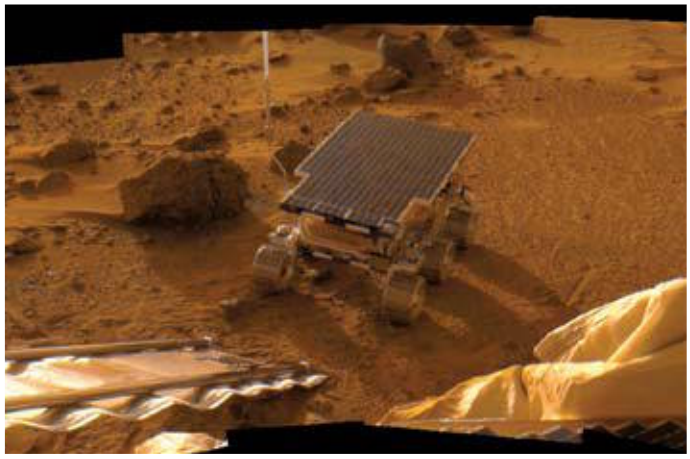
Following the successful Viking landers, the martian surface remained unvisited for more than 20 years. Then, on July 4, 1997, Mars Pathfinder bounced to a landing. NASA designed the spacecraft primarily to test a new method of descending to and landing on the surface. Unlike the Viking landers, in which a descent engine provided the spacecraft's final braking, Mars Pathfinder simply slammed into the surface at about 40 mph (65 km/h). Giant air bags cushioned the impact. After bouncing several times and rolling to a stop, the spacecraft retracted the air bags and unfolded, origami style.

Because Mars Pathfinder was an engineering test-bed mission rather than a true science mission, it carried only three science instruments: an imager, an atmospheric and meteorology package to study daily weather variations, and a spectrometer to determine the chemical compositions of rocks. Another mission goal was to deliver a scale-model rover, named Sojourner, to the surface for engineering tests. The rover was about the size of a microwave oven and sported navigation cameras and the spectrometer. Its mobility allowed mission scientists to analyze many rocks within a short distance of Pathfinder.

The spacecraft landed near the mouth of Ares Vallis, a huge outflow channel near Chryse Planitia, where scientists expected to find a variety of rocks washed down by ancient floods. This provided a good look at a broad area of Mars all in one place. Pathfinder and Sojourner found some of the rocks had a higher silica content than ordinary basalt. The spacecraft also provided support for the idea that ancient floods scoured the surface.

Mars Pathfinder's main scientific goal was to study the variety of rocks, not search for life. Yet the idea of life on Mars does not die

Mars Pathfinder



SOJOURNER STANDS on Mars' surface for the first time. The rover rolled off the Pathfinder platform on just the second day of the mission. The long shadows testify to the lateness of the hour — Sojourner wouldn't start taking data until the next day. NASA/JPL

easily. A little less than a year before Pathfinder set down on Mars, a controversial paper had appeared in the journal *Science*. David McKay of NASA's Johnson Space Center and his coauthors claimed they had found signs of past life in an ancient martian rock. The rock had been blasted off Mars' surface by an impact and found its way to Earth, where it was discovered as a meteorite in Antarctica. Ironically, Mars Pathfinder was the first NASA mission that did not list the search for life as one of its major goals.

Both Mars Pathfinder and Sojourner exceeded their design lifetimes and demonstrated the new technologies would work on future rover missions. The current Mars Exploration Rovers are direct descendents of this modest engineering mission. In another few years, the torch will be passed to even more sophisticated rovers, possibly equipped with biological laboratories. Perhaps then, the timeless question of whether life ever existed on Mars finally will be answered.

Mark Robinson *is a planetary scientist at Northwestern University in Evanston, Illinois.*

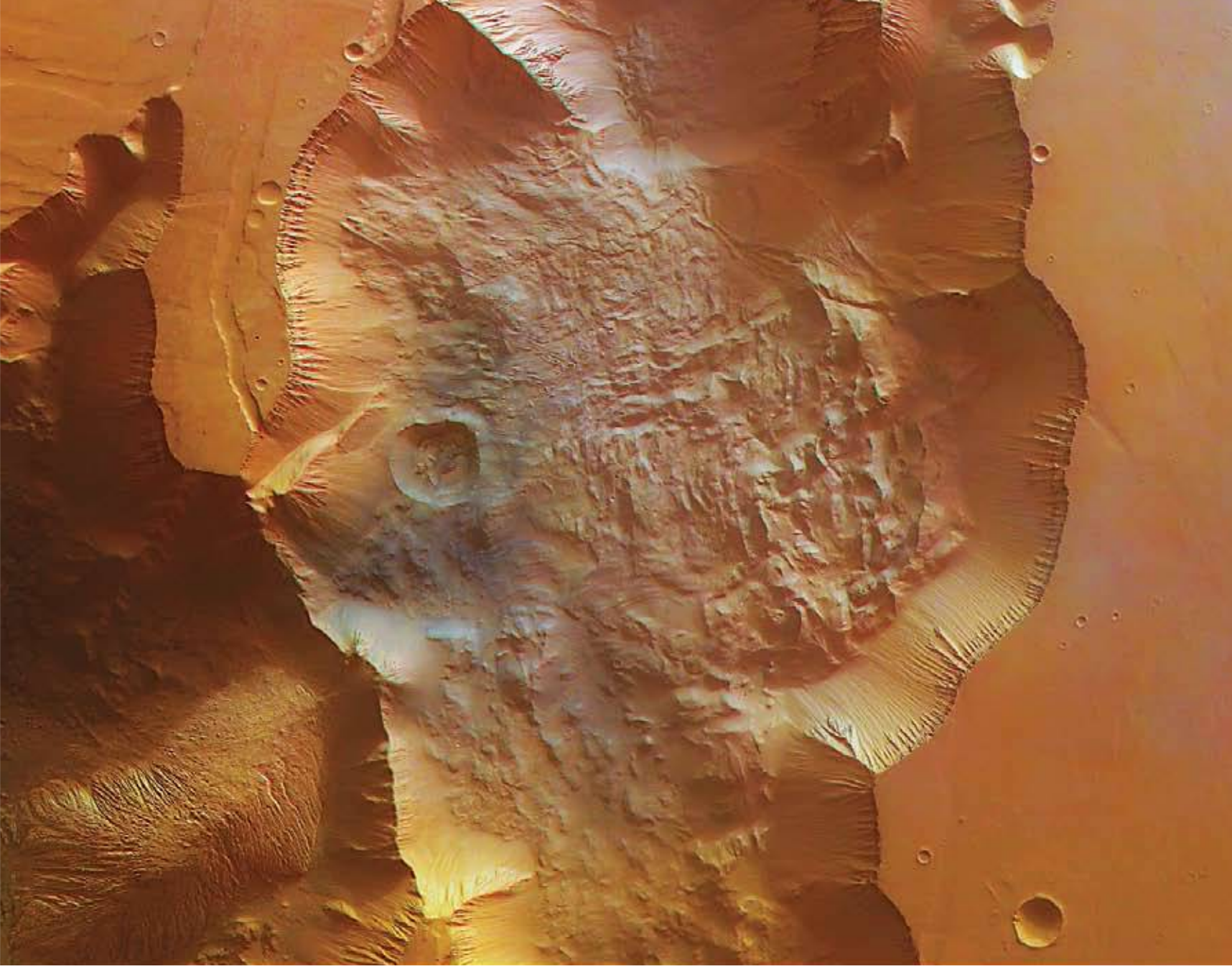
THE VIEW FROM ORBIT

Mimicking what satellites did for Earth in the 1960s, three Mars orbiters are mapping that planet's geography from several hundred miles up.

While landers provide detailed information about their specific sites, it is the orbiting missions that give us global perspectives of how Mars evolved.

NASA's Mars Global Surveyor (MGS) began a three-pronged orbital assault when it swept into Mars orbit September 11, 1997. Mars Odyssey, also a NASA mission, followed October 24, 2001, and the European Space Agency's Mars Express (MEX) arrived December 25, 2003.

The satellites have revolutionized our view of Mars. MGS has delivered high-resolution surface views, the first accurate topographic analysis, details of the planet's shape, the first mineralogical survey, and detection of remnant magnetization in rocks.



Odyssey improved our view of surface features, their properties, and their compositions. It achieved this with visible, infrared, and gamma-ray imaging.

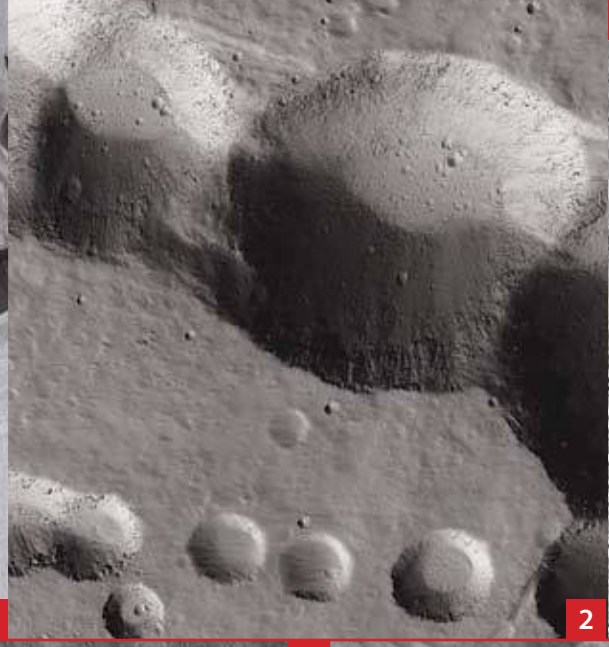
MEX goes even further, with high-resolution stereo surface views and detailed atmospheric studies. With deployment of its ground-penetrating radar in May 2005, MEX provided our first detailed look a few miles below the martian surface. This area is important because it falls well within the region where scientists think ice and possibly water exist.

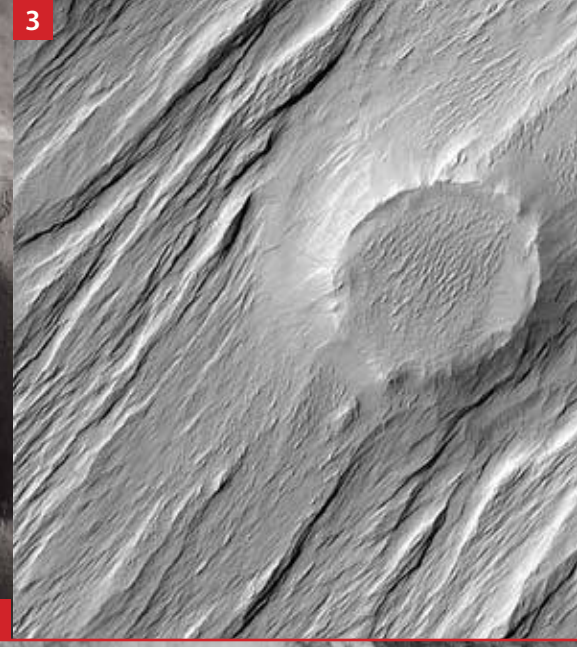
MGS's Mars Orbiter Laser Altimeter (MOLA) found martian elevations as high as 13 miles (21 kilometers) at the shield volcano Olympus Mons to –5 miles (–8 km) in the Hellas impact basin. (Elevations are measured relative to Mars' mean planetary radius of 2,100 miles [3,390 km]).

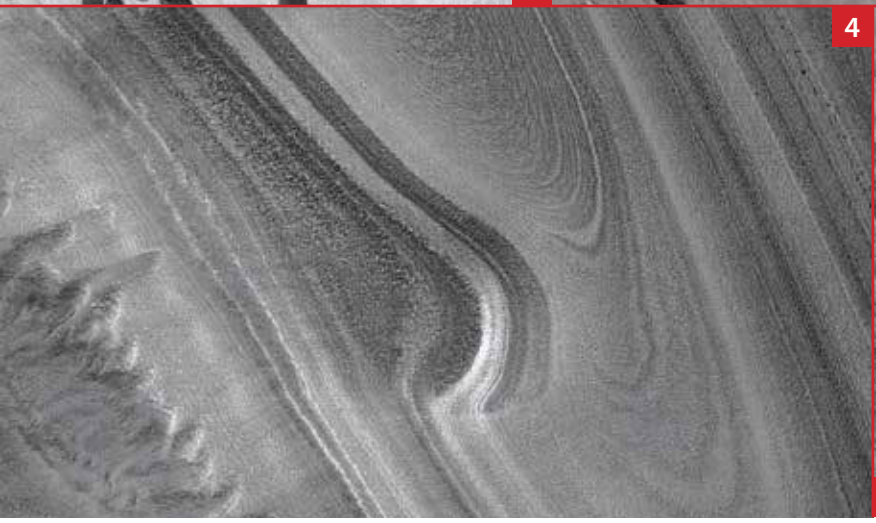
▲TITHONIUM CHASMA is a large trough, roughly 2 miles (3 km) deep and from 6 to 60 miles (10 to 100 km) wide, that lies at the western end of Valles Marineris. This region lies at approximately 5° south latitude and 280° east longitude. Mars Express' HRSC took this image in April 2005. North is to the right. ESA/DLR/FU BERLIN (G. NEUKUM)

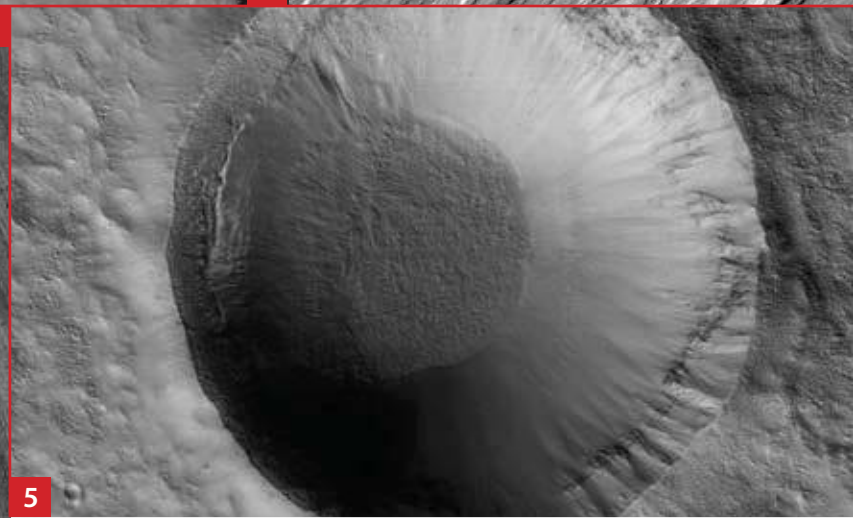
The Red Planet's center of mass is offset about 0.85 mile (1.4 km) in the direction of the Tharsis volcanic region, indicating Tharsis is a several thousand-mile-wide bulge on the planet's surface. MOLA clearly shows the elevation variation between the low-lying northern plains and the southern highlands and suggests this difference results from internal processes rather than large impacts in the north.

MGS's Magnetometer/Electron Reflectometer (MAG/ER) confirmed findings from previous spacecraft — Mars has no active









1 THE MARTIAN POLAR CAP doesn't always cover the surface. During summer, some of the cap sublimates (transforms from its solid state directly to a gas) and materials show through. The Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) imaged Chasma Boreale and revealed dark sand dunes above an eroded, layered surface. NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

2 ASCRAEUS MONS is a large shield volcano (one from which lava flows rather than is blasted out) in the Red Planet's Tharsis region. This MGS MOC image shows both individual and connected sunken areas called collapse pits. Mission scientists can see large, dark boulders on the floors of some of the pits when they examine this image at its highest resolution. NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

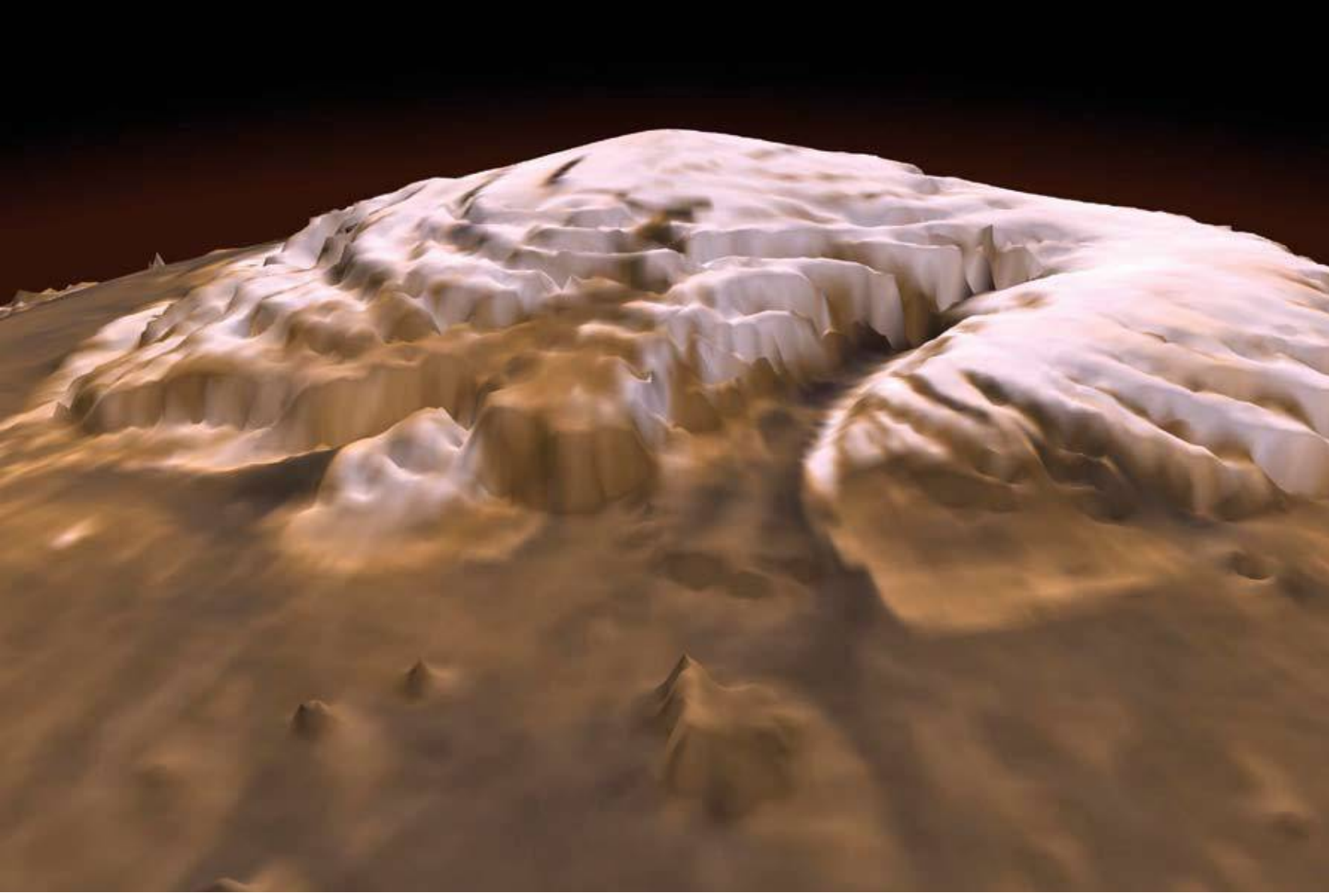
3 A METEOR CRATER in Memnonia Sulci is the large, circular feature in this image. It looks unimposing now, long after martian dust filled and buried it and eons of wind eroded the area around it. The image is about 1.9 miles (3 km) wide. NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

4 NEAR MARS' NORTH POLE, the MGS MOC revealed an area not covered by polar-cap ice. The "stripes" are detailed rock layers. These layers may show climate changes during the past few hundreds of millions of years. NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

5 WINTER ON MARS brings precipitation despite the Red Planet's thin atmosphere. This MGS MOC image shows a southern hemisphere crater with frost on its northern wall (left). NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

magnetic field. However, the instrument detected remnant magnetization in surface rocks, which indicates Mars once had a substantial magnetic field. Almost all magnetic anomalies discovered so far are in the older parts of Mars. This field apparently shut off before the Argyre and Hellas impact basins formed around 4 billion years ago, probably due to cooling of the planet's interior.

MGS's Thermal Emission Spectrometer (TES), Odyssey's Thermal Emission Imaging System (THEMIS), and MEX's Visible and Infrared Mineralogic Mapping Spectrometer (OMEGA) have allowed mission scientists to investigate the composition and physical properties of the martian surface thoroughly. Because martian minerals absorb and then re-radiate heat, this



▲MARS' NORTH POLAR CAP has canyons more than half a mile deep. The MGS MOLA made detailed elevation measurements during the martian spring and summer 1998, and mission scientists combined them into this three-dimensional view. MOLA TEAM/MGS PROJECT/NASA

produces absorption lines in infrared spectra. This allows scientists to determine the planet's surface composition.

Analysis of TES data suggests two main surface compositions: basalt (from volcanic activity), seen primarily in the southern highlands; and a more silica-rich or weathered basalt, seen primarily in the northern plains. A few areas show other compositions, notably Meridiani Planum, which displays a strong hematite signature. Hematite is an iron oxide often formed in the presence of water — it was this mineral signature that led mission planners to select Meridiani as the Opportunity rover's landing site.

The higher resolutions of THEMIS and OMEGA images reveal fine-scale variations in surface composition, including hydrated minerals, sulfates, water ice (in the polar caps), and iron-rich minerals. These results provide better constraints on understanding the planet's geologic history.

THEMIS's infrared capability measures surface temperatures during both day and night. Comparing how quickly particular features cool gives information on their physical properties, particularly particle size. Larger, denser objects take longer to warm up and cool off than smaller, less dense particles. Maps showing temperature variations give scientists information on dust-covered versus rock-covered regions. This information is especially useful in selecting rover landing sites.

Mars' present thin atmosphere prevents water from existing on the surface. However, discovery of channels together with spectroscopic indicators of surface hydrated minerals suggests water previously flowed on Mars.

While most scientists maintain surface water existed 3 to 4 billion years ago, when the atmosphere was thicker, some researchers think Mars has been wet more recently. In the 1990s, several research groups presented evidence of an ocean in the northern plains about a billion years ago.

MOLA imaged Mars' northern plains and revealed their smoothness. The plains are covered by thick deposits of finely

grained material. The best terrestrial analogs for such a surface are sediment-covered ocean basins, lending support to the idea of a previous "Oceanus Borealis."

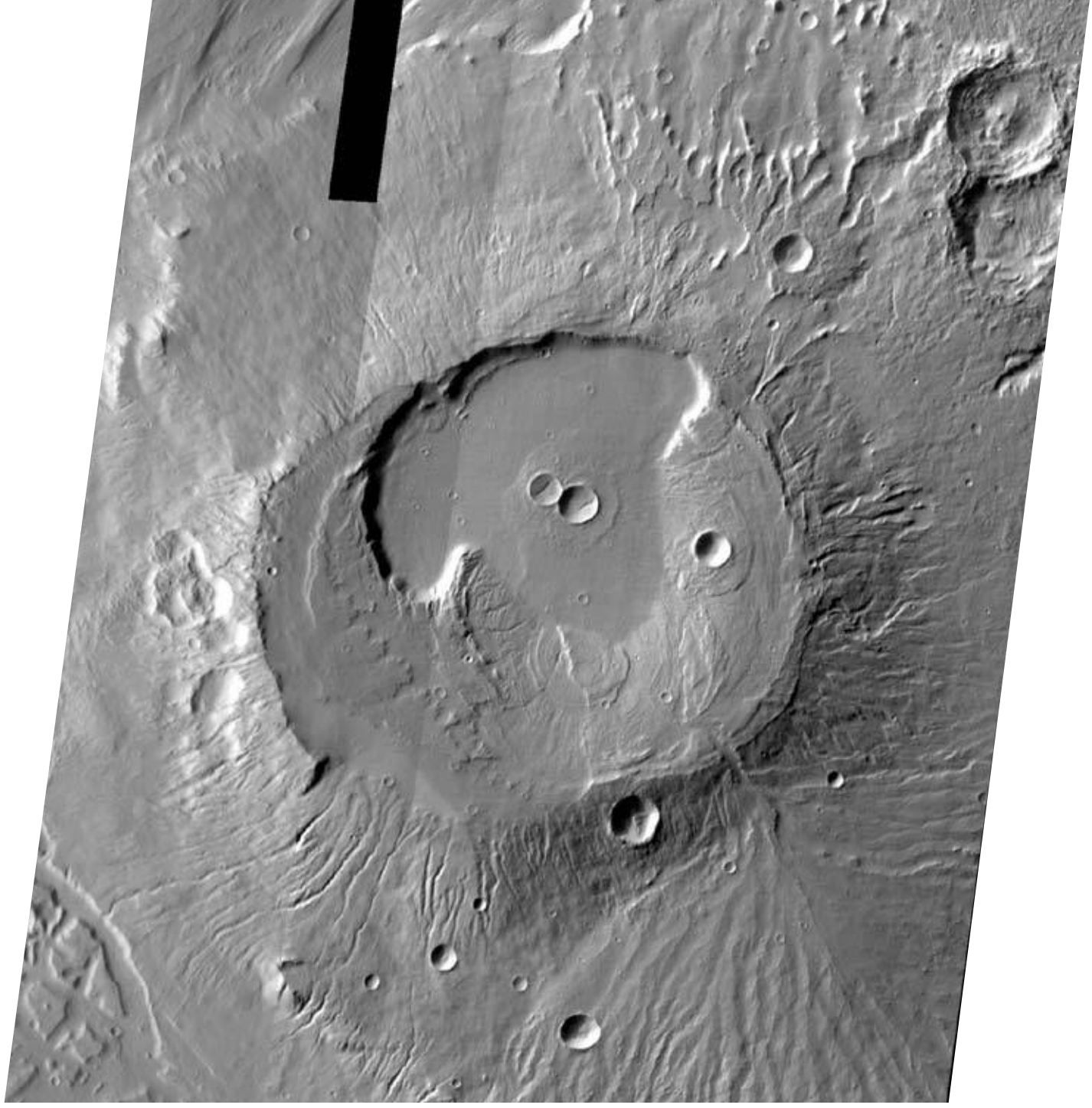
TES, THEMIS, and OMEGA have looked for water-produced minerals, particularly carbonates, which should form when water and Mars' carbon dioxide atmosphere interact. Thus far, no large carbonate deposits have been detected.

Evidence for smaller bodies of water long ago seems a bit stronger. The orbiters have imaged channels that show features indicative of fluid flow. Thick, layered deposits rest on crater floors and in the Valles Marineris canyon system. They show striking similarities to lakebed sedimentary deposits on Earth.

▲ **GLACIERS ROAMED MARS in the past. Mars Express imaged this unusual hourglass-shape structure at latitude 38° south and longitude 104° east. Long ago, a large glacier flowed past the mountains on the right into the smaller crater, filling it nearly to its rim. Then it moved downward into the larger crater.** ESA/DLR/FU BERLIN (G. NEUKUM)

Features resembling fan, or delta, deposits have been identified. Combined with the rovers' results, they argue the martian surface has experienced episodes when water was present.

An unexpected discovery by MGS's Mars Orbiter Camera (MOC) was small gullies on the inner walls of impact craters, channels, and canyons. Gullies appear in the mid-latitude regions and



▲ **APOLLONARIS PATERA is the remains of a volcanic caldera (the large cratered area surrounding where the lava exits) 225 miles north of Gusev Crater, the Spirit rover's landing site. This picture, made by Mars Odyssey's THEMIS, is a mosaic of daytime infrared images. It shows an area 115 miles across.** NASA/JPL/ARIZONA STATE UNIVERSITY

may result from groundwater seepage. The problem is that gullies originate close to the surface, within the depth where models suggest ice, not water, should be present. Some scientists have proposed liquid carbon dioxide or other molecules could be responsible, but the evidence indicates water is the most stable fluid, even under present climatic conditions. An alternate proposal states gullies formed from meltwater during a recent period when snow was deposited on these slopes.

Mars scientists agree the planet has been wetter than previously thought, but was it warm and wet (with water) or cold and wet (with glaciers)? The layered deposits, fan-like features, and channels — combined with the rovers' results — support the idea of flowing water. However, the lack of carbonates and the discovery of the mineral olivine, which weathers rapidly in the presence of water, argue against long periods of wetness.

OMEGA found materials formed within Mars' first billion years show high levels of water-weathering, but younger materials do

OUR SOLAR SYSTEM'S largest planetary surface feature is Valles Marineris, a system of canyons located south of Mars' equator. If on Earth, Valles Marineris would stretch across the continental United States. The individual troughs merge at points that are more than 350 miles (600 km) wide. At its deepest, the canyon floor drops down 6 miles (10 km). NASA/JPL/ARIZONA STATE UNIVERSITY

not. Many of the geologic features studied using MOC, THEMIS, and MEX's High Resolution Stereo Camera (HRSC) bear strong similarities to features formed by glaciers on Earth. Thus, current evidence suggests the formation and movement of ice has been the dominant geologic process for most of martian history, but this has been interspersed with short, warmer episodes when water left its mark, at least locally.

But where is all that water today? Some may still be on the surface, in the form of small glaciers or ice oceans. Some probably migrated to the polar regions. But much of it likely has seeped into the near-surface region. This was confirmed by Odyssey's Gamma Ray Spectrometer (GRS), which detected hydrogen (most likely in the form of water) within the upper 3 feet of the subsurface in several regions. Although scientists disagree about the exact amount of water in these regions, most models estimate ice concentrations of 60 percent or higher in the polar regions and more than 5 percent in the high-hydrogen equatorial regions.

The abundance of ice or water on Mars suggests climatic conditions were different previously. Atmospheric scientists have been focusing on the climatic effects caused by variations in the tilt of Mars' rotation axis. Today, Mars' axis is tipped 25° to its orbital plane. But gravitational effects from the Sun and other planets cause the obliquity to vary from as little as 10° to as much as 80° during about a million years.

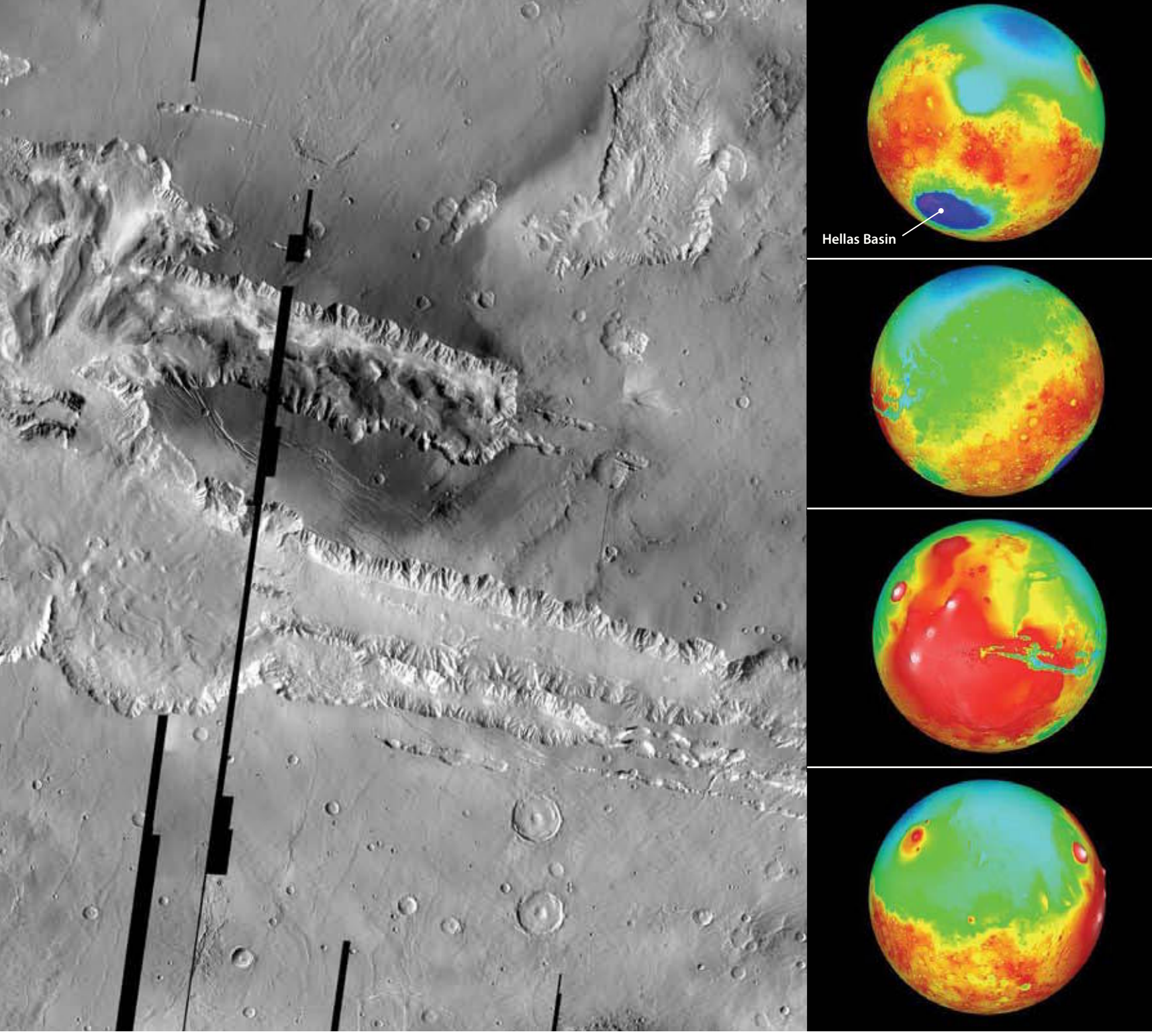
Mars' poles receive more solar radiation at high obliquity, causing polar ices to vaporize. When this happens, the atmosphere becomes more dense, allowing precipitation as rain or snow. Mars apparently is now moving from a high obliquity period, when the glaciers and gullies formed, to a low obliquity period.

The traditional view is that Mars has become less active with time, with the most recent volcanic activity occurring perhaps a billion years ago. This chronology is based on the densities of visible impact craters. The resolutions of imaging instruments on earlier Viking missions were not high enough to discern small craters, so scientists had to limit their age estimates to large regions with many craters.

MOC, THEMIS, and HRSC revealed many small craters across the surface that are being used to provide new age estimates for small regions. Results suggest some of the lava flows in Tharsis and Elysium — as well as some possible water-flow events — are as young as a few tens of millions of years. However, many scientists are leery of such ages because small-crater counts can be contaminated by secondary craters (craters formed by material ejected from the main impacts), which are not evenly distributed across the surface. While the new images provide evidence that Mars has been geologically active in recent times, the exact age of such activity is still debated.

Detection of methane in Mars' atmosphere by MEX's Planetary Fourier Spectrometer (PFS) may give clues to Mars' current state of geologic activity that the surface can only hint at. Methane interacts with oxygen to form water and carbon dioxide in only a few hundred years, so there must be a mechanism replenishing the gas.

Methane concentrations peak in regions where subsurface ice and atmospheric water vapor are prevalent. This suggests interaction between subsurface volcanism and ice is the most likely source of methane production.

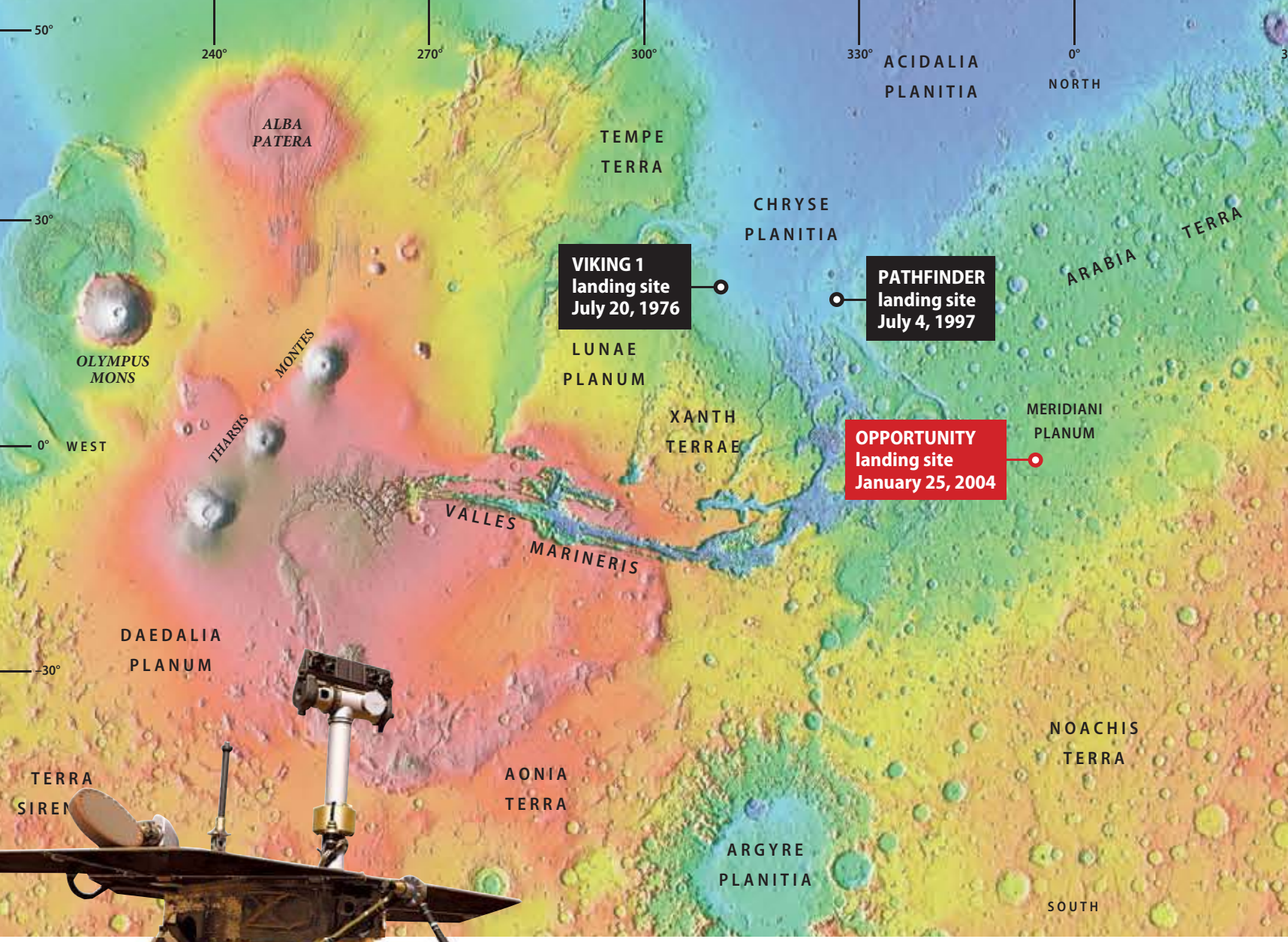


What's next? MGS, Odyssey, and MEX still provide new information, although not all instruments still work. These orbiters and upcoming missions such as NASA's Mars Reconnaissance Orbiter, should continue to dazzle us with news of our neighboring world.

Nadine Barlow *is an assistant professor of physics and astronomy at Northern Arizona University in Flagstaff. She studies martian impact craters to understand the distribution of subsurface water and ice reservoirs and the timing of geologic processes on the planet.*

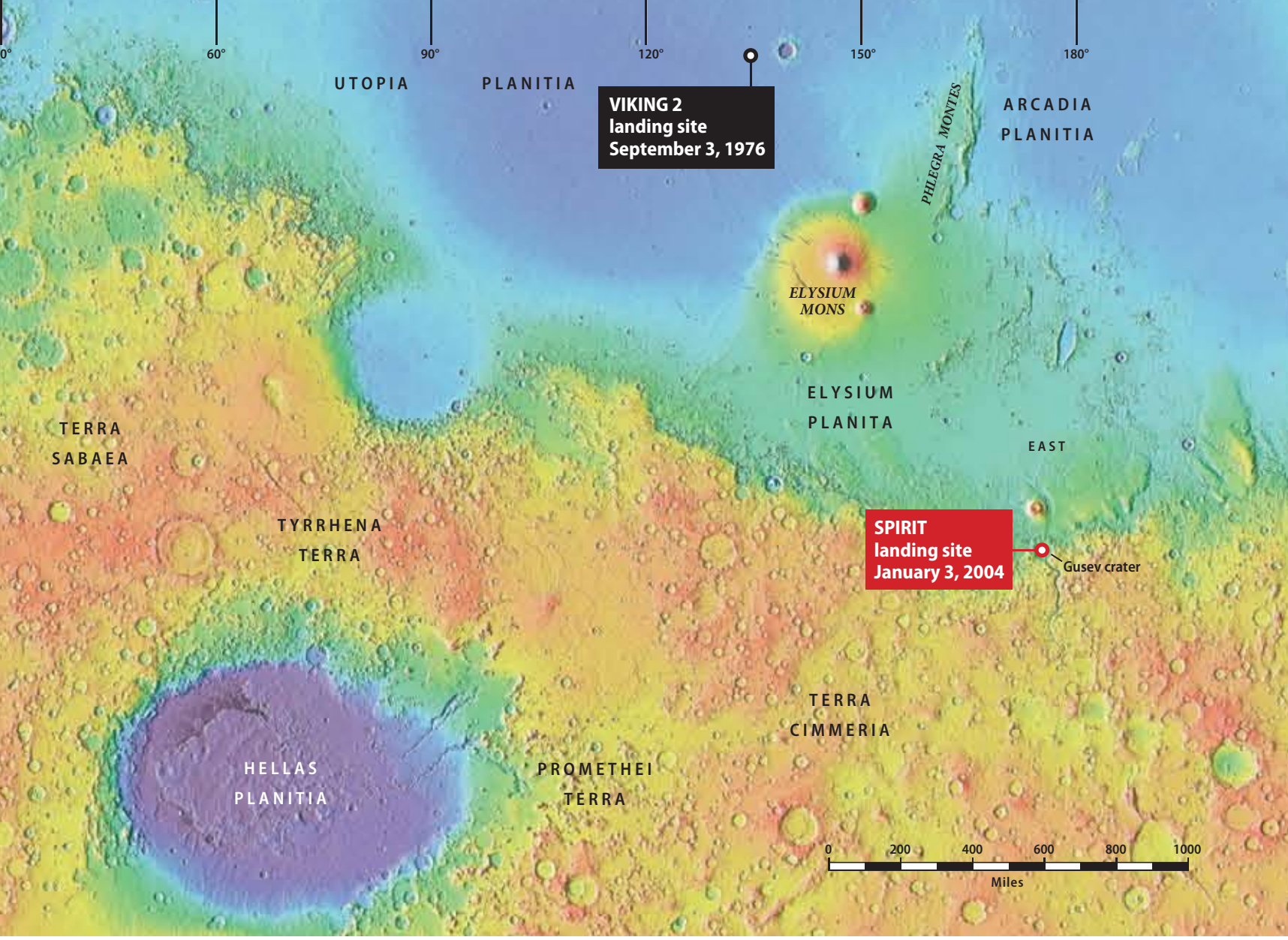
FOUR VIEWS OF MARS, 90° apart, were made by the Mars Orbiter Laser Altimeter (MOLA), which flies aboard the Mars Global Surveyor. Red and yellow indicate higher terrain, and green and blue indicate depressions. To produce these images, MOLA made millions of individual altitude measurements. The most striking feature shown is Hellas Basin (the dark blue oval in the top image). Nearly 6 miles (9 km) deep and 1,300 miles (2,100 km) across, the basin is surrounded by a ring of material thrown out during the impact that created it.

NASA/GODDARD SPACE FLIGHT CENTER/JPL



THE GREAT MARS ROAD TRIP

Two far-ranging rovers have rewritten martian history. BY ROBERT BURNHAM



No one expected they'd last so long. In a classic piece of under-promise and over-deliver, NASA designed the two Mars Exploration Rovers Spirit and Opportunity to survive only 3 Earth months. Yet as this goes to press, each rover has racked up more than 20 months since landing in January 2004, and they have put more than 6 miles (10 kilometers) collectively under their wheels.

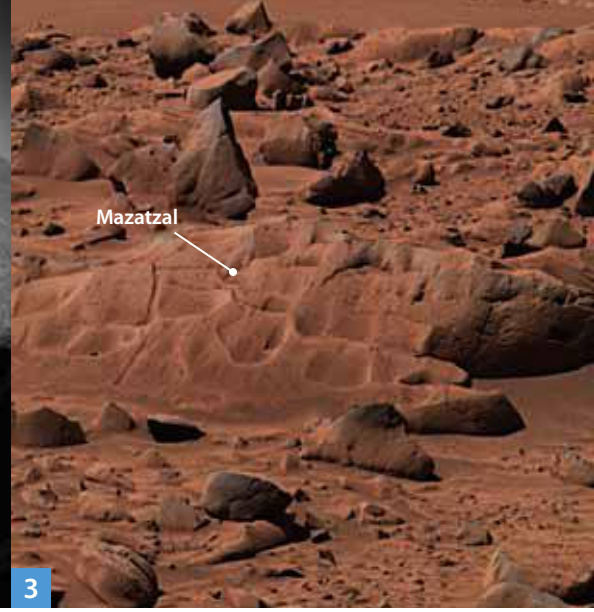
The rovers have driven into and out of big craters, climbed a small hill to study outcrops, experienced dust devils, and gotten themselves stuck and then unstuck. Most important, however, the rovers have found what NASA was looking for. As "Spirit explores Gusev Crater" (page 62) and "Opportunity roves Meridiani Planum" (page 78) make clear, both Spirit and Opportunity have found unmistakable evidence of water-drenched environments in Mars' past.

However and wherever these spacecraft meet their ends, they are the most successful, and publicly engaging, Mars missions ever flown. We won't see their like again until later this decade (or perhaps beyond), when a larger, more powerful, and more capable rover, the Mars Exploration Laboratory, rockets to a landing on the Red Planet's surface (see "Mars or bust," page 94).

The rovers' focus on water reflects NASA's overall strategy for exploring space. Driven by one of the most fundamental questions science can ask — Are we alone in the universe? — NASA is

◀ **SIX WHEELS, several pairs of camera "eyes," and a suite of instruments let each rover act as a substitute for a human geologist. The identical rovers have also taken millions of earthlings along on their travels, through images posted on NASA's web site.** NASA/JPL

▲ **MISSION PLANNERS PUT THE ROVERS down in two spots that looked promising for water. Spirit landed in Gusev Crater, an apparent dry lake bed. Opportunity settled in Meridiani Planum, an area rich in the water-associated mineral hematite.** *ASTRONOMY*: ROEN KELLY, AFTER USGS



"following the water" because however life on Earth began, liquid water was an essential part of the process.

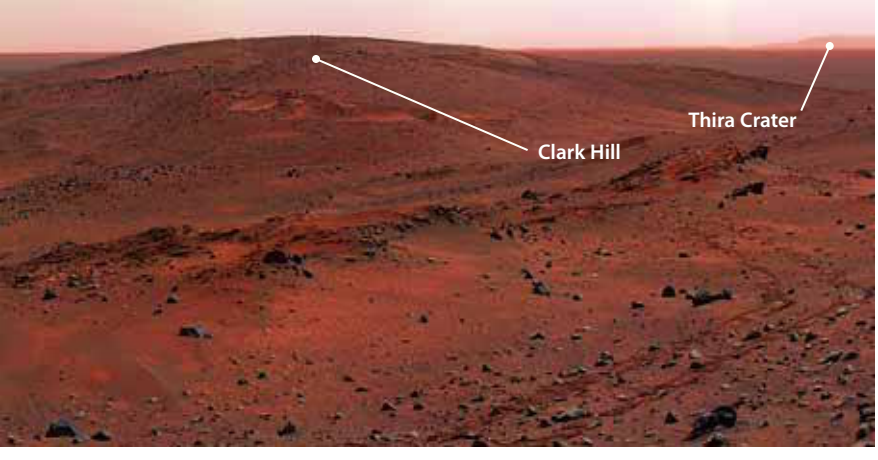
Hunting for niches in the solar system where life may have arisen, NASA is examining places with a high chance of a "wet" pedigree. The two Viking landers in the mid-1970s were sent specifically to look for life's traces in the upper soil.

Their findings were inconclusive at best, in part because the scientists who designed the experiments didn't know exactly what to expect. Moreover, for all their technical sophistication, the landers couldn't move from where they set down. They could pick up only rocks and soil within reach of the 10-foot (3 meter) grappling arm.

The Viking missions — two orbiters in addition to the two landers — achieved a great deal, including high-resolution mapping of the entire planet from orbit. But because the landers didn't find life and, thus, in some sense "failed," NASA found it hard to get funding for many follow-on Mars missions until the 1990s.

In 1997, the Mars Pathfinder mission landed in Ares Vallis with a microwave-oven-size solar-powered rover named Sojourner. Pathfinder — true to its name — pointed a way to explore Mars in a more flexible manner.

The spacecraft pioneered the use of airbags to set down on a planet without using rockets (which can alter the surface). And



1 PEACE ROCK, in the Columbia Hills, proved rich in sulfates and has a porous texture, which suggests ample alteration by water. In this false-color image, taken after Spirit had ground a hole into the rock, blue tones indicate the sulfate material. NASA/JPL/CORNELL

2 WORKING ON METHUSELAH, a rock outcrop in the Columbia Hills, Spirit uses its microscopic imager to make a photo-mosaic of a target dubbed Keystone. NASA/JPL/CORNELL

3 WIND-ERODED FLUTING marks the surface of Mazatzal rock, a piece of basaltic ejecta in Gusev. Mazatzal shows traces of alteration by water, but not to a degree that suggests lots of water. NASA/JPL/CORNELL

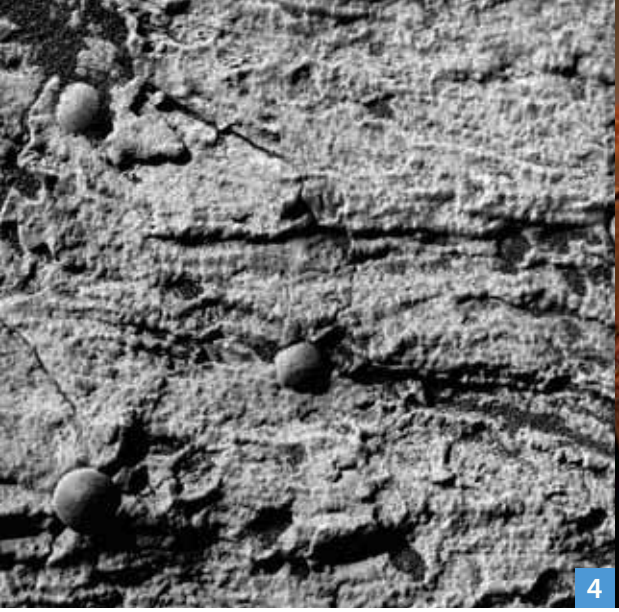
for planetary scientists, Sojourner proved the importance of mobility when its instruments found that rocks just a few feet or yards apart can have different chemistries. After Pathfinder, roving looked highly attractive, because mission planners no longer had to stake the entire mission on whatever lay within the grasp of a fixed lander's robot arm.

When the time came to pick landing sites for Spirit and Opportunity, NASA engaged the world's Mars science community in workshops that began in January 2001, 3 years before the landings. Eight sites made the initial cut and were gradually whittled down to two. One lay in Meridiani Planum, near the zero points of martian latitude and longitude. The other site was in Gusev Crater, almost directly on the opposite side of Mars.

Water, or the promise of it, drove the final choices.

Initially, Gusev Crater looked like a slam dunk. One wall of this 100-mile-diameter (160 km) crater was breached by Ma'adim Vallis, a water-carved outflow channel that drained

◀HIGH IN THE COLUMBIA HILLS, Spirit looked back over its tracks and shot this vista showing Clark Hill at left and the rim of Thira Crater in the far distance at right. The long, low rock outcrop in the foreground has an area scientists dubbed Methuselah at the left end and Larry's Lookout on the right end. NASA/JPL/CORNELL



4 INTERWEAVING LAYERS and round "blueberries" tell a tale of water in motion. Details in this 4-inch-wide cross section in Eagle Crater — Opportunity's landing site — prove a shallow sea covered the region long ago. NASA/JPL/CORNELL

5 INSIDE ENDURANCE CRATER, Opportunity found a wealth of rock layers telling of past eras in martian history. At rear stands Burns Cliff, which the rover explored at close range. NASA/JPL/CORNELL

6 SMALL DEPRESSIONS DOT the surface outside the rim of Endurance Crater. Only a yard wide, the depressions may be scars left by falling debris ejected from the big impact that made Endurance. NASA/JPL/CORNELL

northward into Gusev from a basin in the southern highlands. Scientists studying the crater felt assured it had once been the home of a lake fed by water from Ma'adim Vallis.

The Meridiani site's choice came from orbital mineralogy studies, which identified a large region (as big as Oklahoma) rich in the mineral hematite. This iron-oxide mineral typically forms in association with water, and the quantity seen from orbit suggested the surface rocks and soil contain lots of the mineral.

In a curious reversal of fate, the rover Spirit, the first to land, encountered little sign of water's effects on the rocks at Gusev. But Opportunity, landing 3 weeks later, hit pay dirt immediately. It bounced to a stop in a 70-foot (20m) crater, unpacked its cameras, and found itself facing an outcrop of bedrock that proved to have formed underwater.

Not until 6 months after landing, when Spirit drove up off the lava-covered plain that forms the floor of Gusev, did it encounter rocks that had clearly been altered by contact with water — lots of it. The Columbia Hills, which formed merely a picturesque backdrop to Spirit's initial forays, have become a wonderland of geological interest since Spirit climbed up into them after trekking across the plain.

Opportunity's explorations took it out of the crater it landed in and into a stadium-size crater, named Endurance, half a mile (800m) away. Once inside, Opportunity sampled and drilled its way down the inside wall, identifying half a dozen distinct rock layers, each telling a different story about past martian environments and water's role.

Spirit's future course

lies on and around Husband Hill, where it is exploring outcrops helping us understand the hills' geological structure and history. The robot reached the summit of the hill, which soars 269 feet (82m) above the surrounding plains, in late August 2005. Scientists next plan to drive it over to the southern side of Husband Hill, where orbital views suggest it will find an area with many layered rocks.

Opportunity's course lies southward, as scientists are driving it into the so-called Etched Terrain. Orbital imaging hints this area consists of light-colored outcrops of bedrock, but how its rocks relate to the layers already examined is unknown.

Beyond lies Victoria Crater, 5 times wider and deeper than Endurance. It sits on the far side of the Etched Terrain, and getting there requires mission controllers to find a safe route through the terrain — or a path around it.

Once at Victoria, scientists will study the crater from the rim, gauging its slopes and surveying its rock exposures. Is there a route down the inside wall? And just as important: Once inside, can Opportunity get out again?

Just as Spirit has, Opportunity has done so well and exceeded its designed lifetime by so long that it seems greedy to plan what might follow exploring Victoria Crater.

But why should Opportunity's mission end in Victoria? Vast tracts of unexplored land still lie before both rovers.

It's unclear how long the rovers will last — either could die at any point through mechanical or electronic failure, or from dust building up on the solar cells, reducing power below the survival point. But as long as Earth-built wheels can leave tracks on Mars, the rovers' mission will continue.

And who knows? Maybe the greatest discoveries to be made by Spirit and Opportunity still lie ahead.

Robert Burnham *is a senior editor of* Astronomy.

SPIRIT EXPLORES GUSEV

After a 7-month trip from Earth through space and finally the martian atmosphere, an airbag-covered rover named Spirit bounced and rolled its way into Gusev Crater January 3, 2004. For the team of planetary scientists at the Jet Propulsion Laboratory (JPL) in Pasadena, California, a few tense minutes passed while the critical information about Spirit's fate raced through space at the speed of light.

Mission scientist John Grant remembers the jittery tension in the air as his team waited. Finally, when word reached them of the spacecraft's safe arrival, the adrenaline rush came, too. Spirit's mission had begun!

The first Mars Exploration Rover (MER) to touch down, Spirit faced the sweeping panorama of an open crater. As the mission began, a bit of trouble reared its head. The descent from the landing platform proved challenging, as a partially deflated airbag blocked the main driving ramp. Fortunately, a side ramp allowed Spirit its first contact with the Red Planet's surface.

CRATER

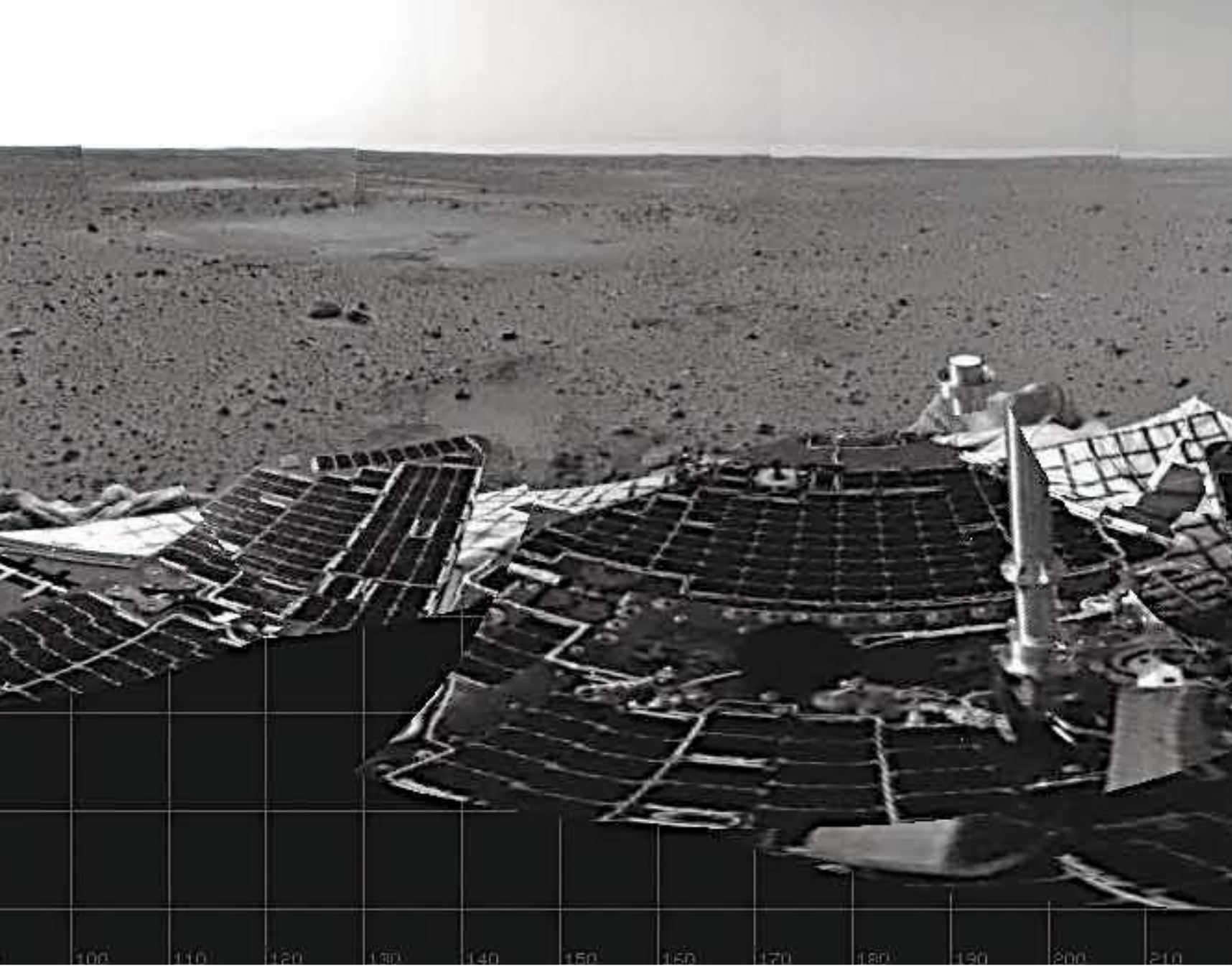
From the moment it landed, this rover has been living up to its name. Spirit has traveled many times the planned distance of 600 meters, fighting solar-panel dust buildup (that threatened to cut its power to zero), a gimpy wheel, martian winter, and long drives across plains and up hills. Unlike its twin, Opportunity, Spirit didn't catch any early breaks.

Spirit's team had to work out crippling software kinks as well as the challenges of its location — what turned out to be a lava bed. The team never gave up on Spirit's ability to find evidence of water in Gusev Crater, and the robot has shown team members and others what it's capable of. Spirit has persevered this long with the help of good design and a team of resourceful and enterprising scientists and engineers.

During those initial days, the team learned how to reach targets and measure rocks. But within days of starting out, Spirit faced a mission-threatening software problem. On January 21, 2004, which was sol (martian day) 18, JPL lost control of the rover for several days as Spirit's computers continually rebooted. Many feared the mission was over. After mission control found the flaw in the rover's flash memory and devised a workaround solution, the machine soon was up and running.

▲LOTS OF INDIVIDUAL FRAMES make up each martian panorama imaged by instruments aboard the Spirit rover. The Cahokia mosaic, which was the first 360° panorama taken at the Columbia Hills, consists of 470 images through six camera filters taken from August 9–19, 2004 (sol 213–sol 223). It took 14 sols to downlink all the data for this panorama to Earth. The final approximate true-color image required several more weeks of image processing and geometric mapping by mission scientists. NASA/JPL/CORNELL

Initial data from the landing site told a different story than the one gleaned from orbit. From above, the surface appears to be an ancient, dry lakebed with indentations from past flowing streams.



▲ THE MARTIAN DAY immediately following Spirit's bouncing and rolling landing was January 4, 2004 (sol 2). This mosaic, taken by the navigation camera, shows a 360° panoramic view of the rover and the surrounding surface. NASA/JPL

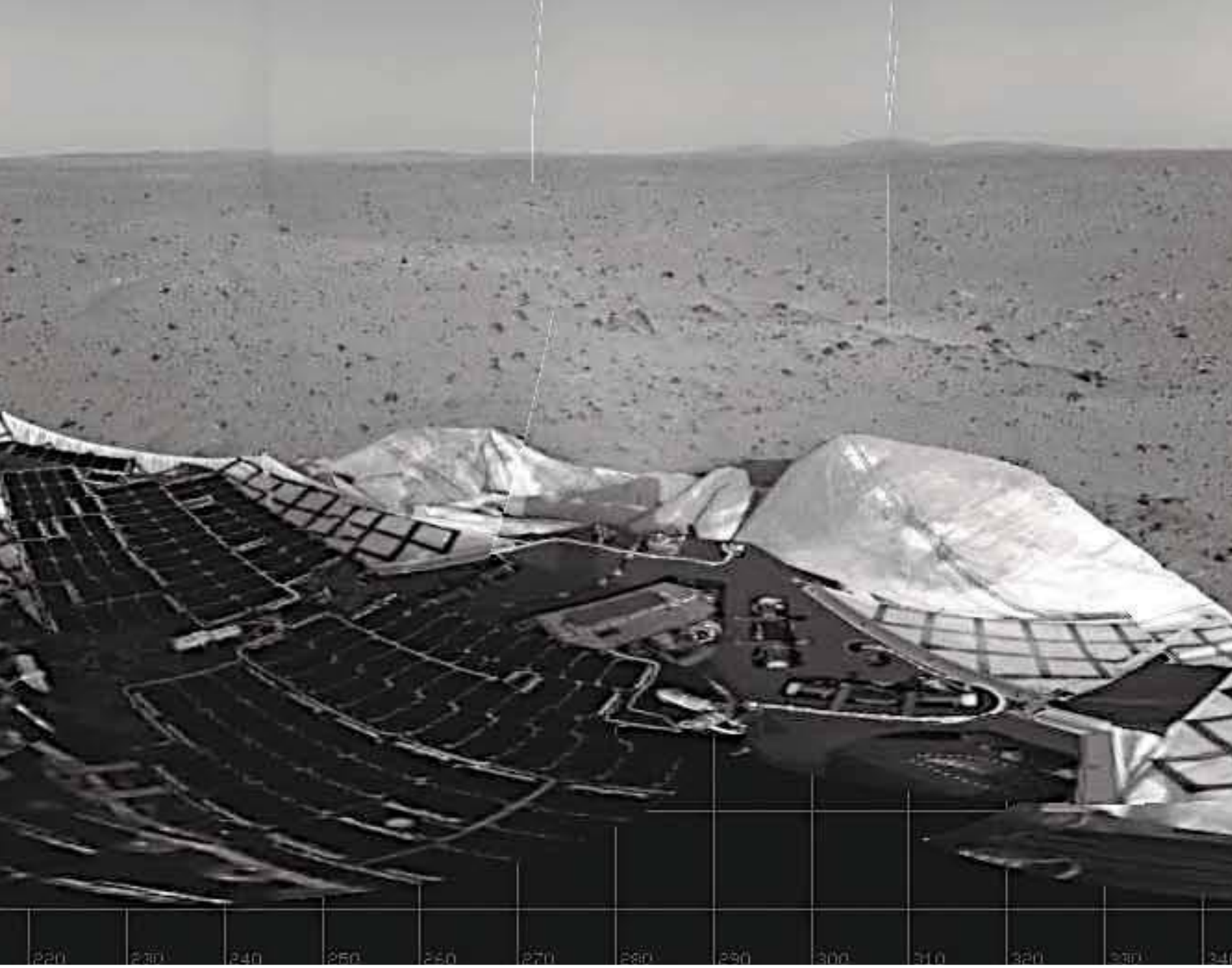
After examining the rocks, the science team found basalt and other minerals consistent with flowing lava, but no evidence for significant amounts of water. "We came to realize that we'd been faked out by Mars," says Steve Squyres of Cornell University, principal investigator for both Spirit and Opportunity.

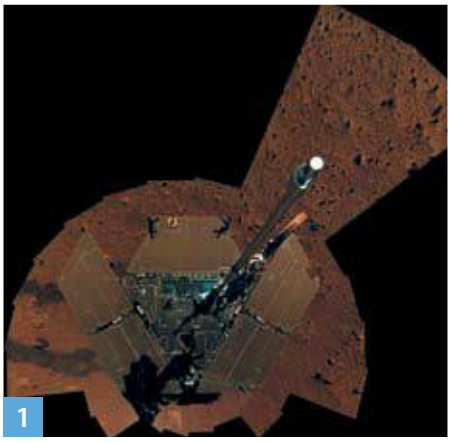
With this knowledge, Spirit started its journey to Bonneville Crater, about 330 yards (300 meters) from the landing site. Bonneville, about 275 yards (250 meters) wide, appeared to be an impact crater that could reveal older, water-influenced geology

1 A SELF-PORTRAIT gives mission scientists an overview of the rover's exterior. Spirit's panoramic camera took the images that form this picture December 4 and 5, 2004 (sols 329 and 330). NASA/JPL/CORNELL

2 SPIRIT'S HAND contains the rock abrasion tool (RAT). Here, it's in front of Adirondack. Before drilling into this rock, Spirit cleaned off a portion with the RAT's stainless-steel brush. Spirit's panoramic camera took this image February 6, 2004 (sol 36). NASA/JPL/CORNELL

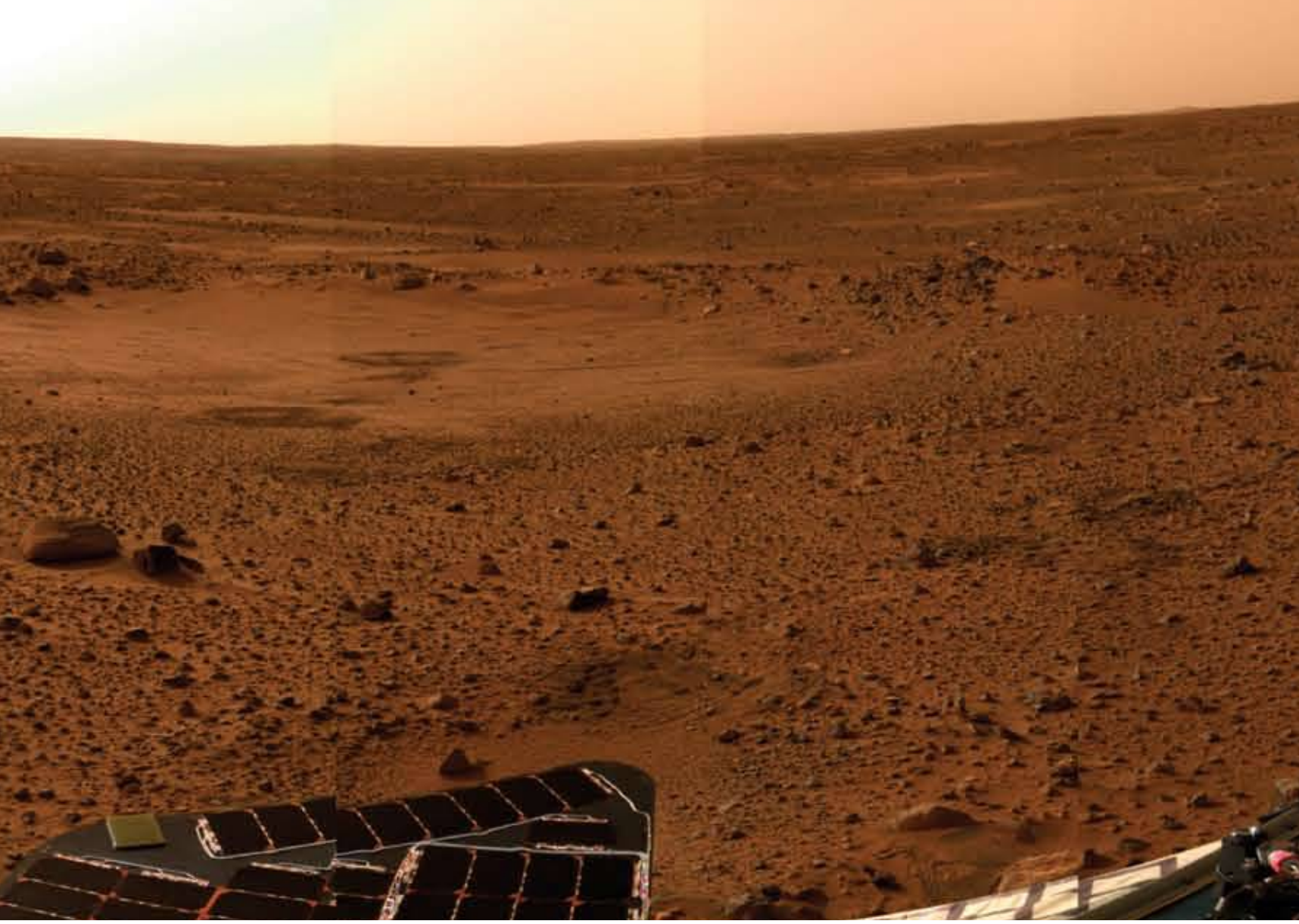
3 A PUZZLING PATCH of soil intrigued mission scientists after Spirit rolled off its platform — the Columbia Memorial Station. They used Spirit's panoramic camera to take this image January 14, 2004 (sol 12). Spirit detected the mineral olivine and discovered the soil is more cohesive than expected. NASA/JPL/CORNELL




1

2

3



▲ **DARK MARKINGS to the left may be surface disturbances caused by the bouncing, airbag-encased lander. The horizon appears sloped because of the tilt of the lander's deck. Spirit took this image January 7, 2004 (sol 5).** NASA/JPL/CORNELL

from below the surface. After 60 more sols in Gusev, Spirit found little evidence of previous water there.

Jet Propulsion Laboratory scientist Matt Golombek was the science operations working-group chair when Spirit stood at the edge of Bonneville. "I remember in the press conference trying not to sound disappointed because when we looked in we saw no layers of sedimentary materials whatsoever," he says. Although the team had learned about volcanic Mars from the basalt found in the plain, the mission through its expected lifetime — 90 sols — had not given any clues to water in the past.

The initial mission met all of its official criteria for days of operation, distance driven, and number of rocks examined. The MER team then could have settled for scooting around Bonneville or examining other similar basaltic rocks near Spirit's landing site. However, the team reached a quick consensus: The best chance for discovering evidence of water lay in the Columbia Hills.

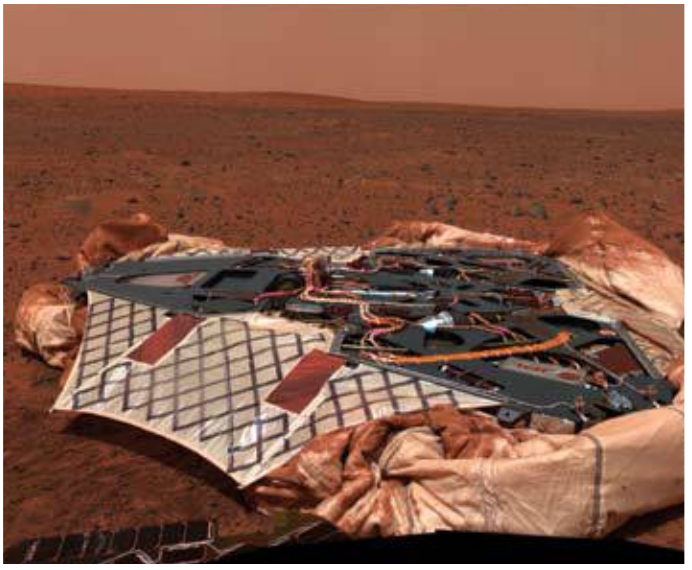
After a difficult journey of about 330 yards (300 meters) to Bonneville, a planned drive of more than 1.2 miles (2 kilometers) was audacious, but carefully calculated. Spirit looked to the horizon and started off.

Adding drama to the decision to drive toward the Columbia Hills, no one could predict how much longer Spirit would last. "If you had given me truth serum before we landed," Squyres says, "I would have told you more than 90 — 120 — 150 — maybe if everything goes our way, we can squeeze 180 sols." Faced with uncertainty, the team maximized each day with the rover, looking forward to all it could tell scientists about the Red Planet's surface.

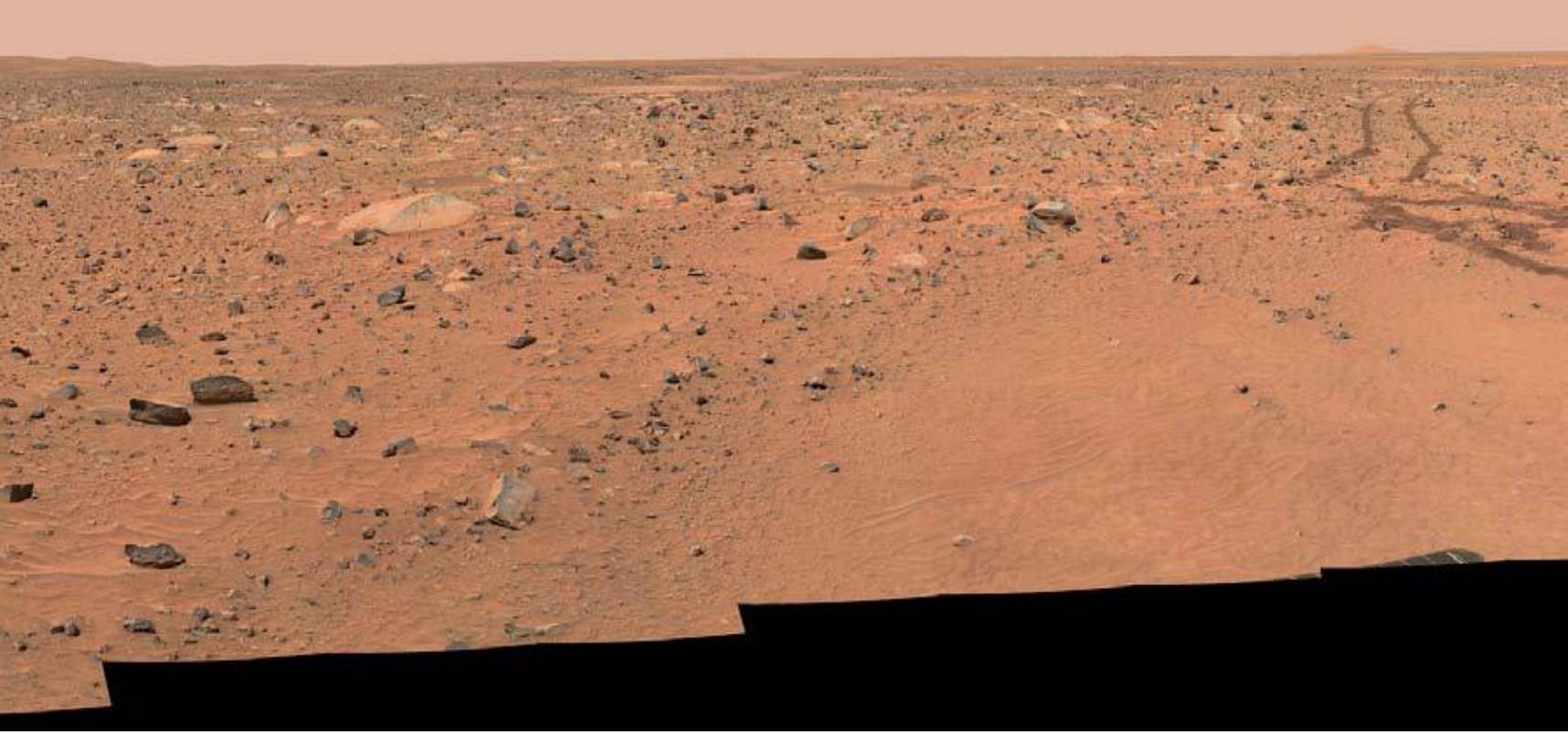
On June 12 (sol 157), by moving a single meter, Spirit crossed a barrier into new territory, as the rover left the volcanic

plains and discovered a more ancient geology mission scientists believe was influenced by water. One of the first rocks that gave mission scientists clues to past martian water was the appropriately named "Pot of Gold," an unusually shaped rock enriched with sulfur, bromine, and chlorine. Its distinctive spokes were capped with nuggets of hematite, a mineral that, on Earth, often forms in the presence of water.

In addition, hill-driving was a new game for the mission team. Ray Arvidson, MER deputy principal investigator, remembers the week of hard work around sol 160 that he and the mission team put into reaching Pot of Gold.

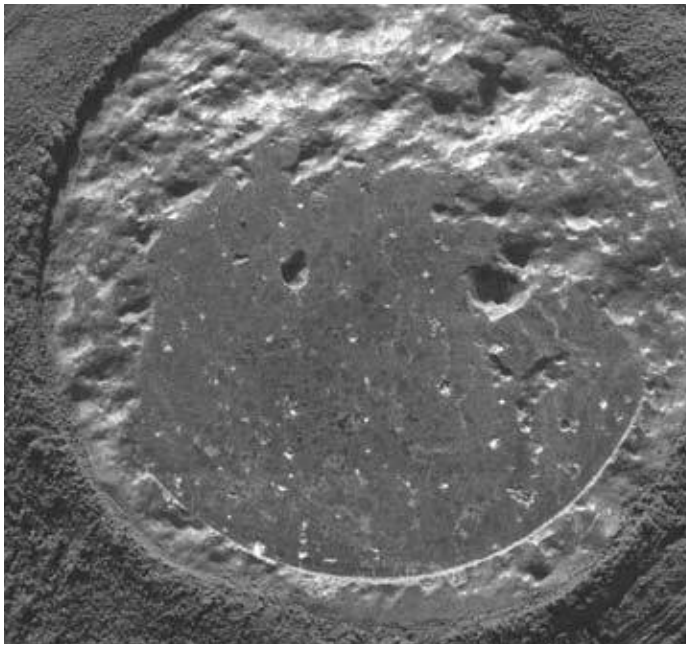


"OFF AND RUNNING" was the feeling mission scientists had when Spirit finally rolled off the Columbia Memorial Station in Gusev Crater. The ridge of the rover's next destination, Bonneville Crater, can be glimpsed to the upper left. To the right are the East Hills, about 2 miles from the landing site. Spirit took this image January 18/19, 2004 (sol 16). NASA/JPL/CORNELL



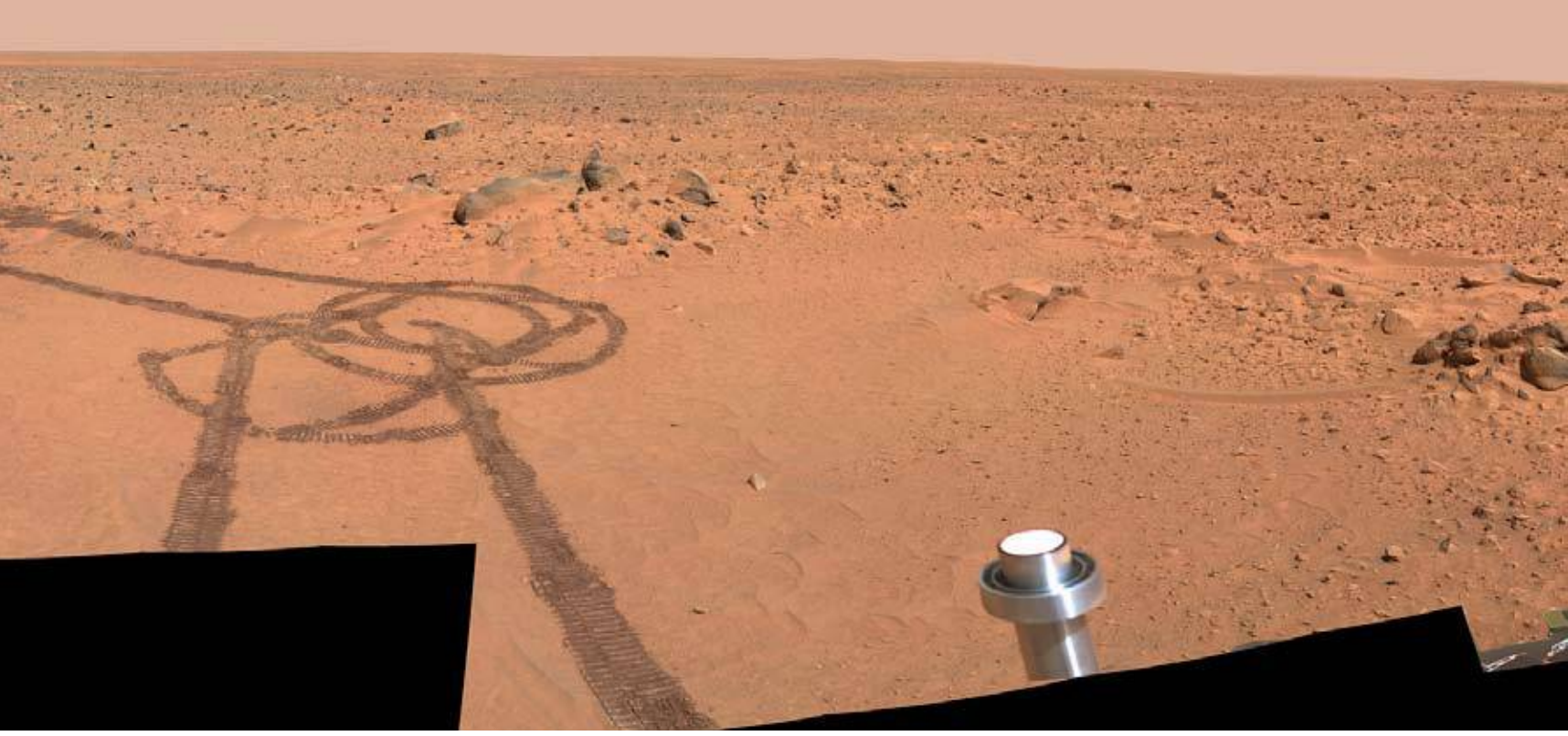
▲ **ON THE WAY TO BONNEVILLE CRATER, Spirit crossed from smooth plains to rocky material ejected from Bonneville when the crater formed. This composite image from Spirit's panoramic camera spans 360° and comprises 78 images taken from different camera positions March 3–5, 2004 (sols 59 through 61).** NASA/JPL/CORNELL

▼ **SPIRIT'S ROCK ABRASION TOOL drilled a 2-inch hole into a rock named Humphrey March 7, 2004 (sol 61). The veins within the rock may be evidence that water trickled through the material when it was deep underground.** NASA/JPL/CORNELL/USGS/HONEYBEE ROBOTICS



"Imagine walking on a 20° slope with a lot of loose rocks and loose soil, and you slip and slide all over the place," Arvidson says. "And then it turned out that it was a wonderful rock in terms of really providing the information that we needed — we were no

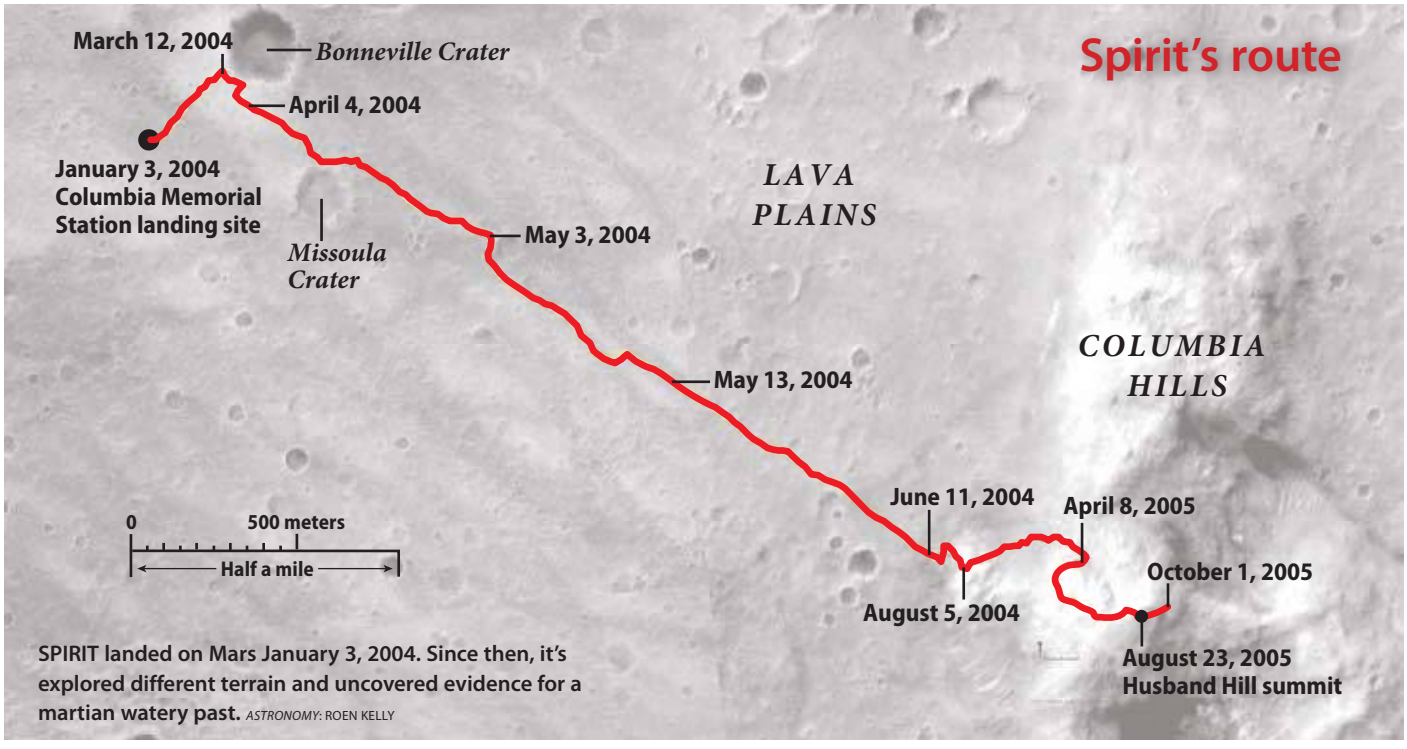
▼ **ONE OF THREE THEORIES is correct about this unusually flaky rock named Mimi: It was subjected to pressure deep underground; it received a pressure shock from an impact; or it was a dune cemented into flaky layers by a process that involved water. Spirit took this image February 10, 2004 (sol 40).** NASA/JPL/CORNELL



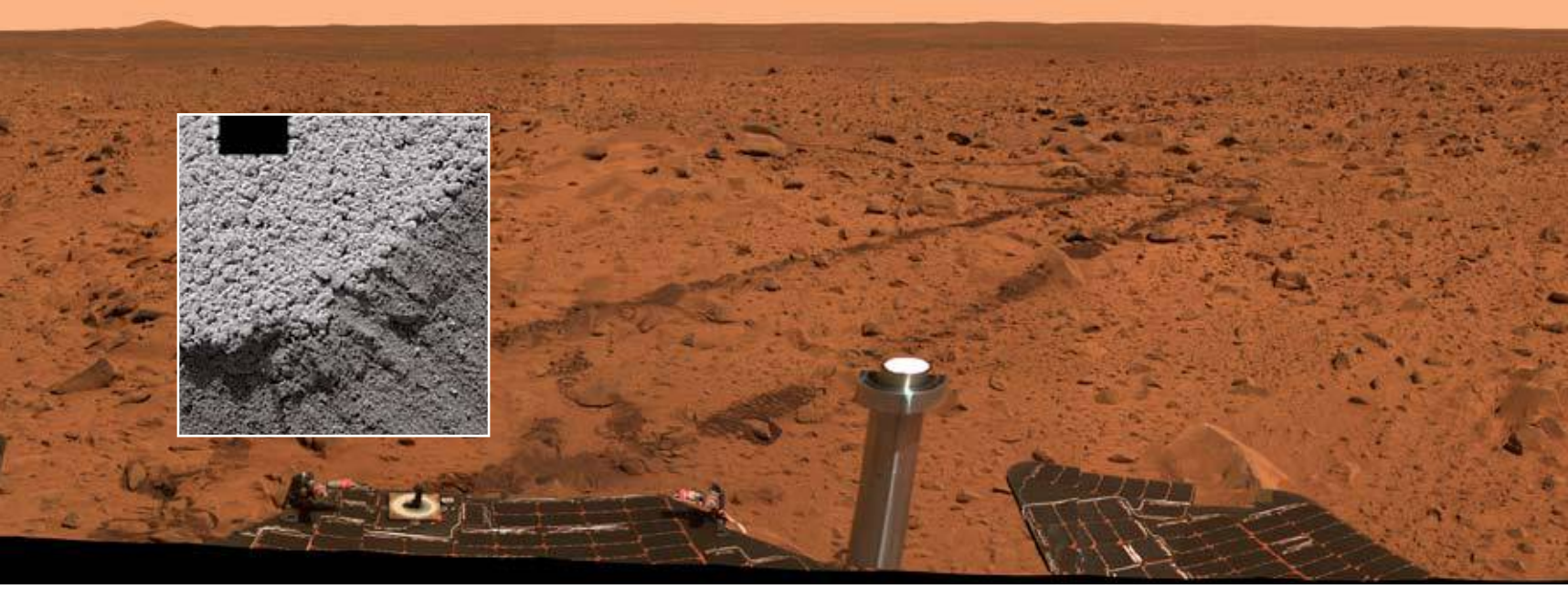
longer looking at iron-bearing basalts but rocks that have been corroded and enhanced in hematite, enhanced in sulfur, bromine, and chlorine."

Just as the geology was getting more interesting for Spirit, concerns about the vehicle and the logistics of keeping it running began to resurface. At the same time the rover arrived at Pot of Gold, engineers noticed the right front wheel was drawing twice as much electric current as the others.

Concerned the lubrication might have leaked, the team began to favor the wheel either by dragging it or by driving the rover backward. During the weeks and months that followed, the wheel's problem lessened, and the mission team no longer is concerned it



SPIRIT landed on Mars January 3, 2004. Since then, it's explored different terrain and uncovered evidence for a martian watery past. *ASTRONOMY:* ROEN KELLY



▲ **(Inset) SERPENT DRIFT is a tiny area captured by Spirit's microscopic imager March 19, 2004 (sol 73). Scientists are puzzled by the fine grains making up the drift's interior that are 4 times smaller than similar sand grains found in drifts on Earth. Particles as small as those in Serpent Drift would be spread out as dust on Earth. Note: The black box in the image resulted from missing data.** NASA/JPL/CORNELL/USGS

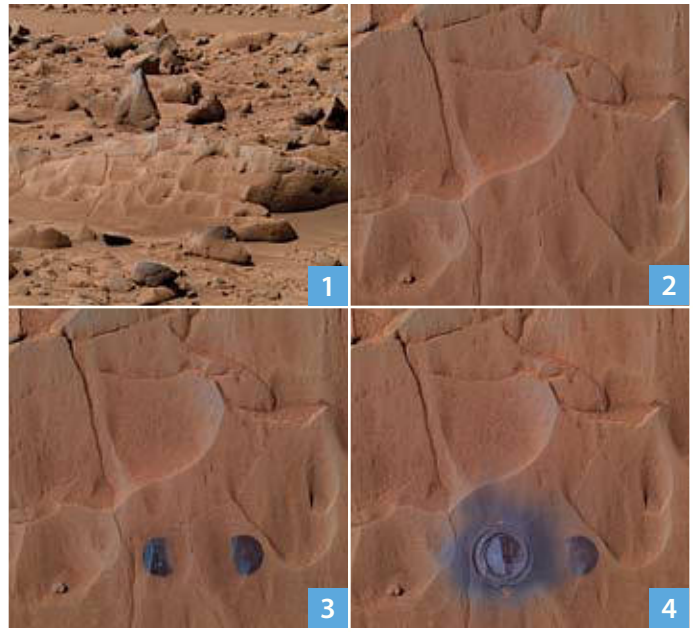
▲ **(Panorama) BONNEVILLE CRATER was the first major target that mission scientists directed Spirit toward. It arrived there March 11, 2004 (sol 67), and made this panorama the next day. Bonneville is about 800 feet in diameter and lies roughly 1,000 feet from Spirit's landing site. Mission scientists hoped Bonneville would reveal older, water-influenced geology, but Spirit found only basalt and no sedimentary layers. In addition to the crater's rim and interior, you can see Spirit's tracks and part of the rover itself.** NASA/JPL/CORNELL

will cripple the vehicle. Driving backward has proven so successful for maintaining even wear and tear on all parts of the rover that both Spirit and Opportunity now spend almost equal time driving forward and backward.

Martian winter posed the next challenge, as Spirit faced a grueling climb up Husband Hill, positioned at 15° south latitude. The approaching winter threatened Spirit's power source because the Sun would be lower in the sky.

Already limited by the buildup of almost 200 sols' worth of dust on its solar panels, a lack of adequate solar energy could have forced Spirit into hibernation and an uncertain future. But using martian topography to the rover's advantage, the team kept Spirit on sunward-facing slopes to maximize the available solar energy.

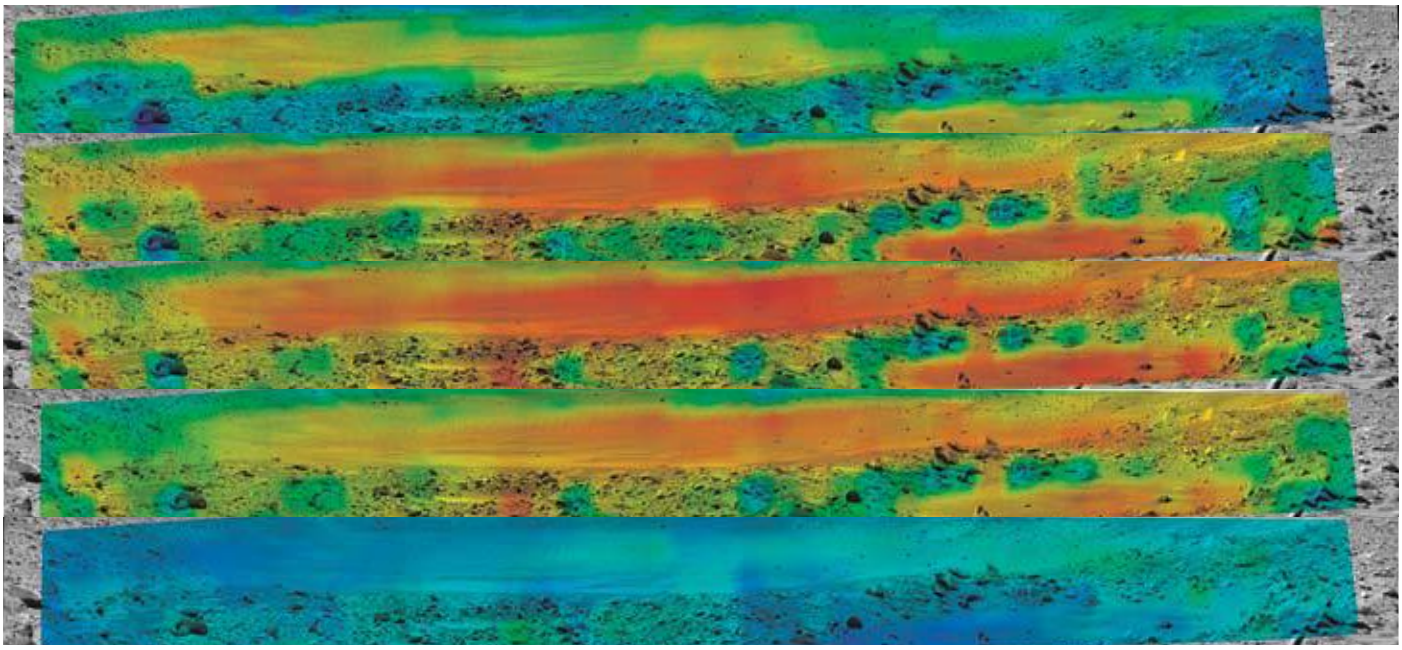
At almost twice its original expected lifetime, Spirit began its climb up the Columbia Hills. Unlike the tidier geological narrative of Meridiani Planum being studied by Opportunity, the geology here is still a "complex, jumbled-up mess," says science team member Doug Ming. But it is a geology with an ancient water history, and from the beginning of the climb, the team knew Mars was presenting it with a subtle and complicated puzzle.



▲ **GRINDING A ROCK is slow when the work is directed from millions of miles away. 1 Spirit's panoramic camera took this image of the rock Mazatzal, which was covered with a light coating of red dust. Mission scientists think fluid may have been present at its formation. 2 On March 24, 2004 (sol 78), Spirit's panoramic camera took this image of untouched Mazatzal. 3 On March 27 (sol 81), Spirit's RAT brushed two areas of Mazatzal — New York (left) and Illinois. 4 On March 28 (sol 82), Spirit's RAT drilled 0.15 inch into New York. The right side of the hole shows the dark coating revealed by brushing. The left side shows the underlying basalt.** NASA/JPL/CORNELL

"Basically, all the rocks we have found in the Columbia Hills show evidence of having interacted with liquid water," Squyres says.

From the first major climb up the West Spur of Husband Hill, Spirit has uncovered the violent and mysterious past of this part of



Mars. Rocks here were formed from a volcanic explosion or some kind of impact.

On the West Spur, those exploded bits settled into layers through air or possibly water to form sediments. But water transformed the mineralogy and chemistry of these rocks.

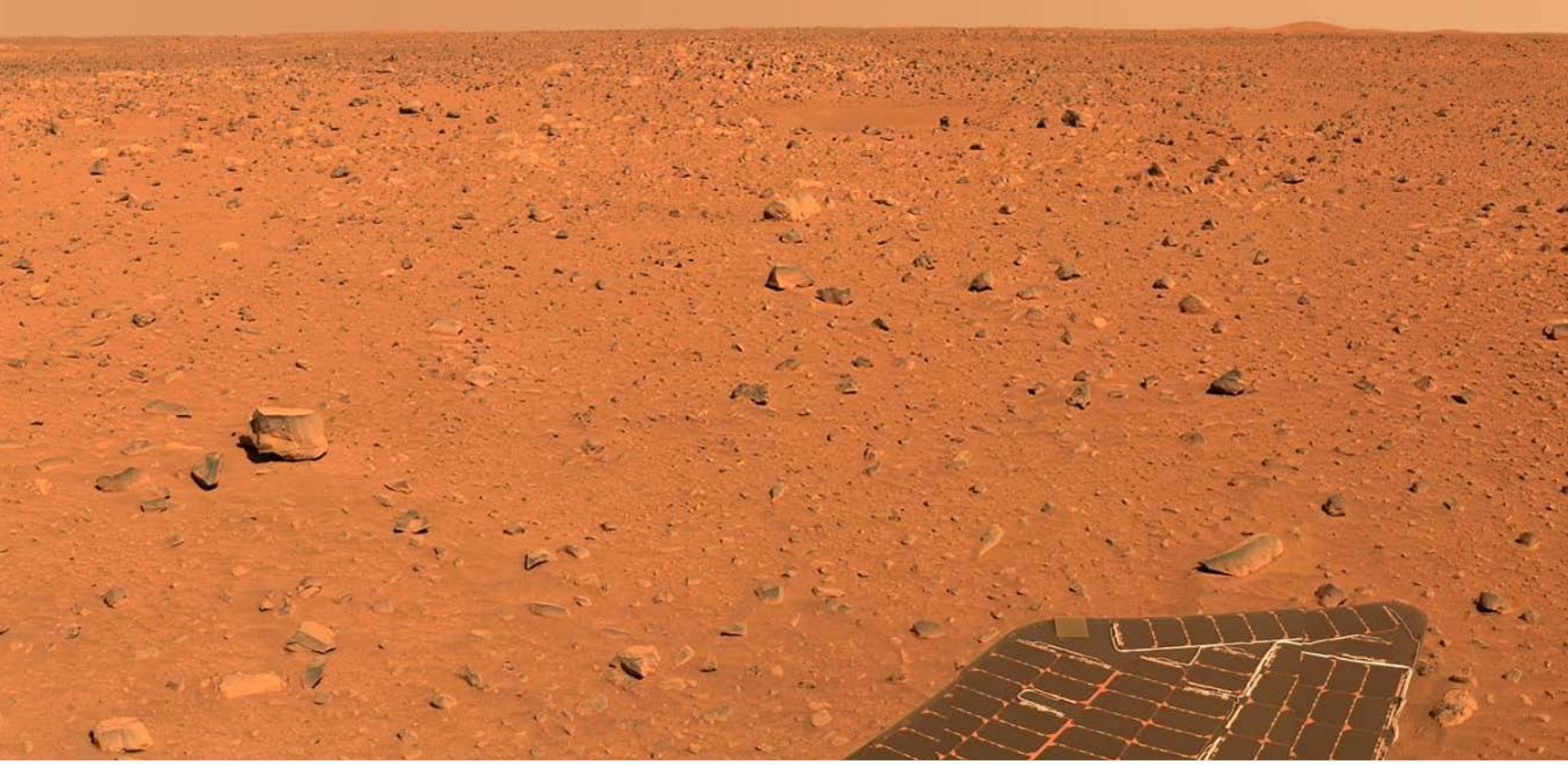
Spirit found evidence for goethite, an iron oxide mineral that requires liquid water to form. Many of these rocks also contain high concentrations of sulfur, chlorine, and bromine that liquid water would have carried and deposited within these rocks.

The rocks are soft, as if an acidic groundwater source percolated through them and corroded their insides. Farther up Husband Hill, on Cumberland Ridge, the rocks have a similar texture to those below but have a higher phosphorus content.

"Maybe the most interesting rock of all that we've found is one that forms some of the bedrock on the flank of the hill," Squyres says. "And it's basically a sandstone: grains of basaltic sand that are cemented together with magnesium sulfate salts, which is fascinating stuff." Water must have been present for such salty glue to form, and the science team is on the lookout for more of this type of rock.

The rocks found so far also mix grains of minerals and glassy material, suggesting a violent origin. Scientists think the rocks in

▲THIS TEMPERATURE MAP of Bonneville Crater shows how the surface temperature changes throughout the day and may indicate differences in particle size. In this sequence, quick reddening during the day suggests small particles like sand or dust. A blue area later in the day is indicative of larger rocks. Red in these images is approximately 27° F, and blue is –45° F. Frames were taken May 3, 2004 (sol 118), at (top to bottom) 10:15 A.M., 11:49 A.M., 1:35 P.M., 2:35 P.M., and 4:39 P.M. local solar time at Spirit's location. NASA/JPL/CORNELL/ASU



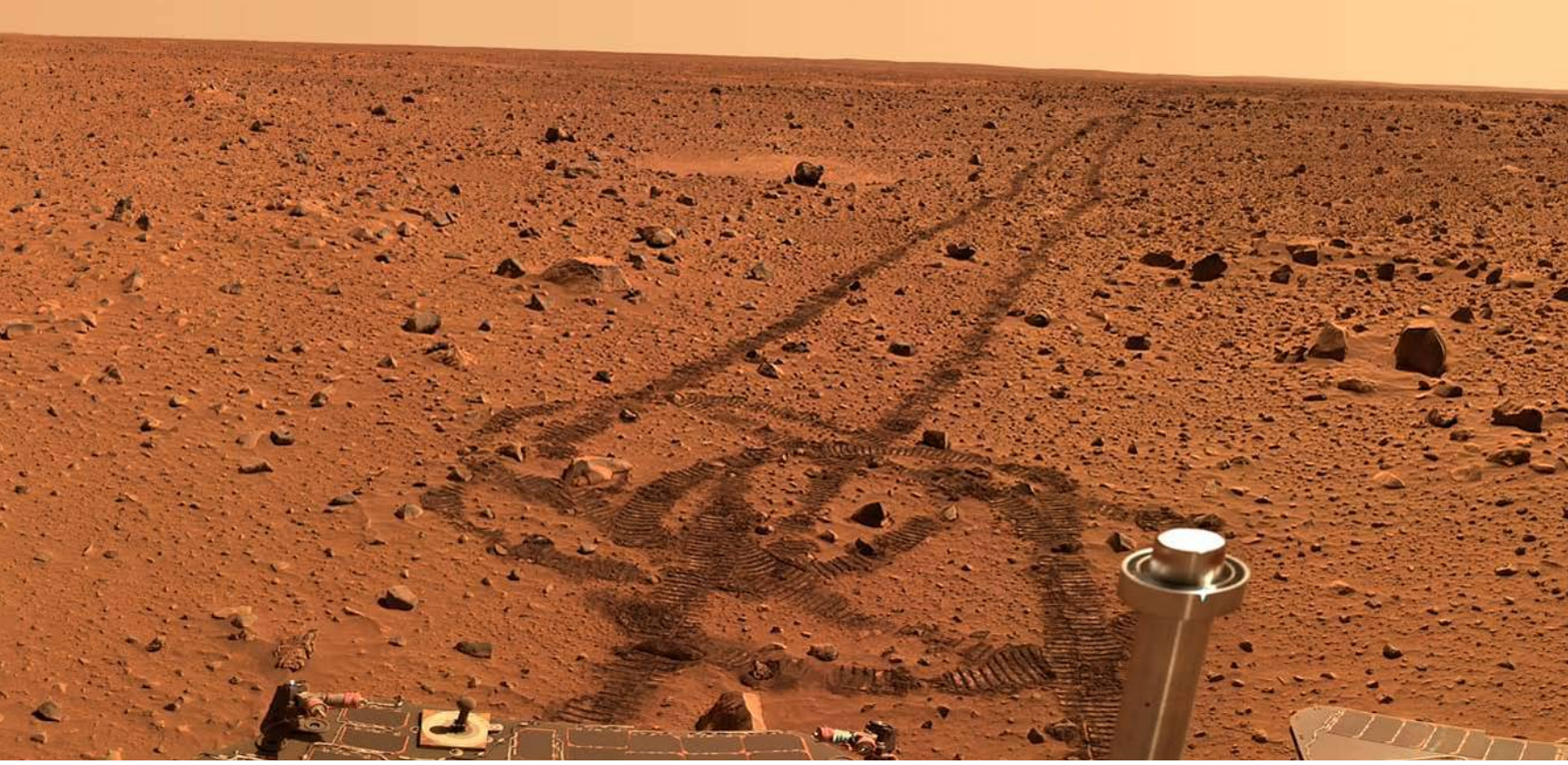
▲ **(Panorama) SANTA ANITA was identified from orbit by the Mars Odyssey thermal imaging system as an area that heats up and cools off quickly because it's dusty. Rocks heat up more slowly but also retain heat longer. This panorama was compiled from images taken May 21, 25, and 26, 2004 (sols 137, 141, and 142).** NASA/JPL/CORNELL

▲ **LAHONTAN CRATER, 230 feet in diameter, is the highlight of this mosaic, taken May 5, 2004 (sol 120). Spirit's navigation camera took three images that scientists stitched together into a 120° panorama. Note the wind-ripple feature in the foreground.** NASA/JPL

the Columbia Hills formed either when a large volcano erupted or a large meteorite crashed into the martian surface.

With the rover slipping and sliding up 20° slopes in the depths of martian winter, the team had to be careful using power for both experiments and driving. Dust continued to accumulate on the rover throughout its journey, and Spirit's 900 watt-hours of energy at landing had dwindled to less than 400 by March 7, 2005 (sol 418). Then in martian spring, the team was trying to reach the summit of Husband Hill by sol 500 to use topography again as an advantage and maximize the summer Sun.

Knowing Spirit cannot survive below 270 watt-hours, the team figured the end was near. Reaching the summit of Husband Hill became the latest of the rover's challenges. Also, Mars had its own



▲ **FANCIFUL NAMES like Pot of Gold and Rotten Rocks are short descriptors that provide a look into mission scientists' thoughts. Pot of Gold is an unusual, nodule-covered rock scientists hope will provide new insights into martian chemistry. Rotten Rocks resemble rotting loaves of bread — their insides are eroded, leaving only their "crusts." These images were taken June 13 and 14, 2004 (sols 158 and 159).** NASA/JPL/CORNELL

▶ **THE STRING OF PEARLS is a set of bright spots imaged by Spirit's microscopic imager. As the rover traveled, Spirit's wheels broke open rocks in an area called Hanks Hollow and revealed the spots. This image was taken July 2, 2004 (sol 177).** NASA/JPL/USGS

ideas: A dust storm was moving through Gusev. Although not mission-threatening, when coupled with the lower power and the slow progress up the hill, the storm was an unwelcome obstacle.

On sol 420, the energy suddenly spiked, and Spirit woke up 2 hours earlier than expected. Miraculously, gusts of wind from the storm had blown most of the dust off Spirit's solar panels, and the rover now had more power than the mission team had figured out how to use.

The next day's science operations meeting buzzed with Spirit's new energy, Grant says. The rover was up to more than 800 watt-hours, a level not observed since sol 30.

Despite the power surge, Squyres warned the science team that Spirit still had hundreds of sols of wear and tear. Cautious optimism continued to guide the climb up the side of Husband Hill, but the added power afforded a few luxuries.

1

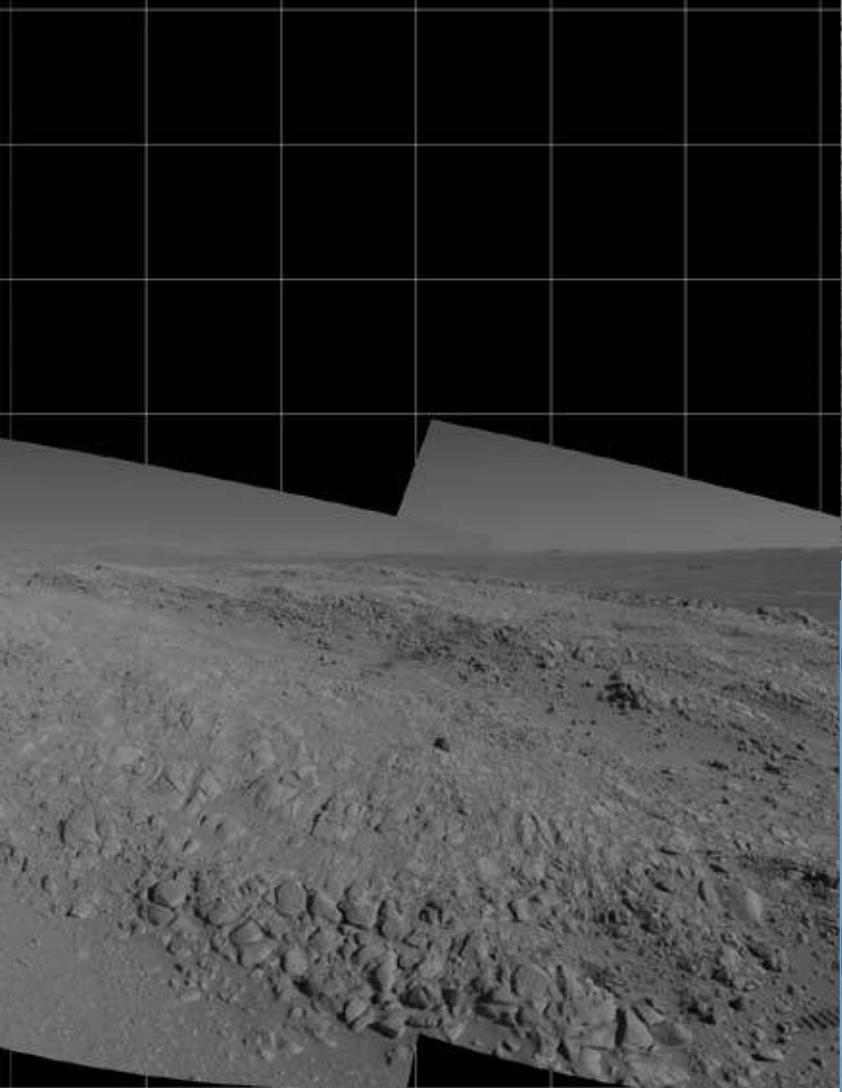
"That's the first time in 400 sols on two rovers that we've ever gone back to a place that we've been. It was so good that we just had to." — *Steve Squyres*

A few sols before the dust storm reached Spirit's location, the rover reached a soil patch called Paso Robles. After slipping and sliding in the dirt while trying to climb the hill, the rover's wheels churned up a bright white powder. The strange sand provoked enough interest that the team decided to break out the robot arm and do some chemical analysis before driving on.

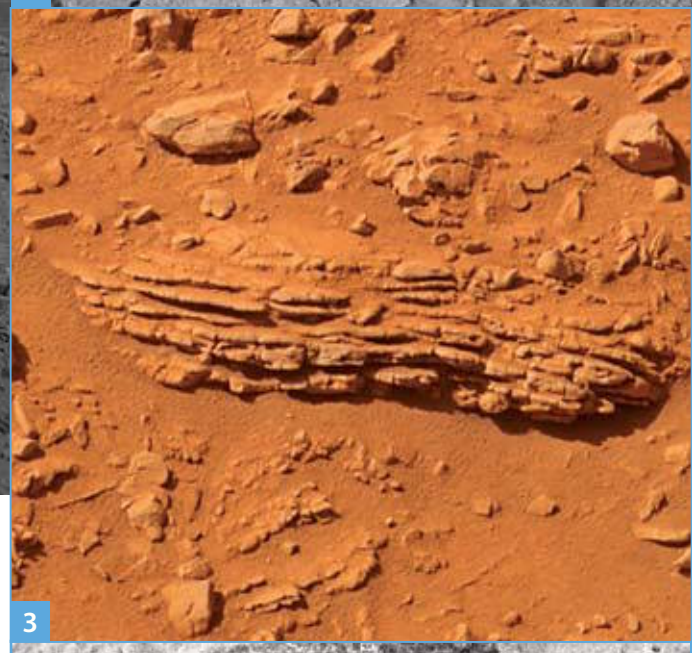
In the meantime, the rover continued to slip, but the elemental chemistry results were anything but disappointing: The unusual sand was 60-percent salt, mostly ferric (iron) sulfates. Then the mission team got the call from scientists in Germany, who also were analyzing the data, confirming 30-percent sulfur oxide content. "This is the highest sulfur concentration we've ever seen on Mars," Squyres says.

As Spirit moved on to the crest of Cumberland Ridge, the science team analyzed the data from Paso Robles and decided to reexamine the salty soil. "That's the first time in 400 sols on two rovers that we've ever gone back to a place that we've been," Squyres says. "It was so good that we just had to."

But what does this scrambled geology mean for the history of Gusev? The science team is still trying to put together the whole



2



3

4

1 SPIRIT took this 360° image October 7, 2004 (sol 271). At this point, Spirit had traveled 2.26 miles (3.6 km), 6 times the distance mission planners had set as the criterion for success. NASA/JPL

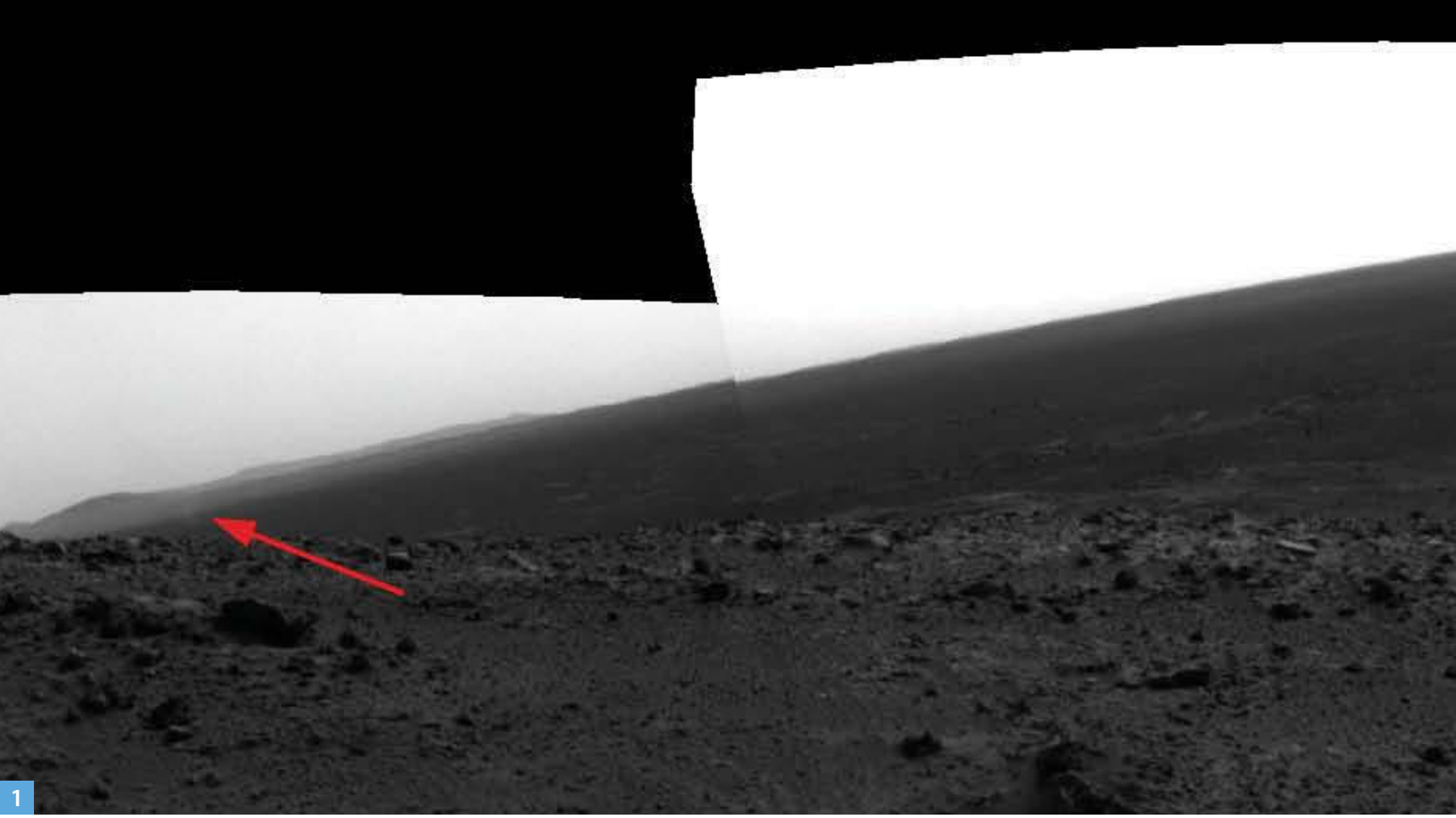
2 CLUMPY SOIL imaged by Spirit's microscopic imager November 19, 2004 (sol 314), shows a light-colored material scientists think is dust that fell out of Mars' atmosphere. NASA/JPL/CORNELL/USGS

3 TETL is a layered rock about 10 inches long. Spirit's panoramic camera examined it September 29, 2004 (sol 264). NASA/JPL/CORNELL

4 WISHSTONE is a rock with light and dark material imaged December 9, 2004 (sol 333) with Spirit's microscopic imager. NASA/JPL/CORNELL/USGS

story, and other scientists agree: They need more bedrock. Without it, they lack the critical context to see how the varied rocks in the Columbia Hills relate to each other. So, as Spirit continued its climb up Husband Hill, the scientists hoped the trek down the opposite side and into the valley below would fill the gaps of their incomplete picture of the Columbia Hills.

And that puzzle will shed light on the larger question of whether life could have existed on Mars. NASA long-term planner Dave



DesMarais thinks Spirit will come close to establishing that a potentially habitable subsurface environment exists on Mars. The ferric salts Spirit found point to a potential energy source for life through oxidation of iron. But iron oxidation makes only a small amount of energy, so the questions become 1) how long water might have persisted and 2) whether life would have had time to evolve and adapt. "If the evidence of water is so pervasive, if it persisted for a long period of time, we could have seen where life could have lived there," he says.

If current estimates are correct, the area around Gusev had salty and acidic subsurface water between 3 and 4 billion years ago, before some cataclysmic event led to the dry Mars we see today. In addition, although most scientists had expected to see martian carbonates, the team has not found them. Sulfur and sulfates dominate the geology at both Gusev Crater and on Meridiani Planum.

Although Spirit's mission presents a jumbled picture that's still unfolding, Gusev might be a key for understanding much of the planet. "Gusev Crater is probably much more representative of Mars as a whole," Squyres says. "It's kind of [a] blue collar, working class, everyday kind of Mars."

Both rovers, in fact, have raised the bar for robotic achievements. It's enough to warm a planetary geologist's heart.

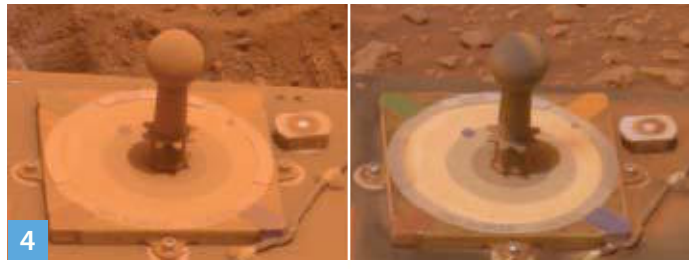
Sarah Webb *is a freelance science writer in New York City and a former chemistry researcher in both the United States and Germany.*

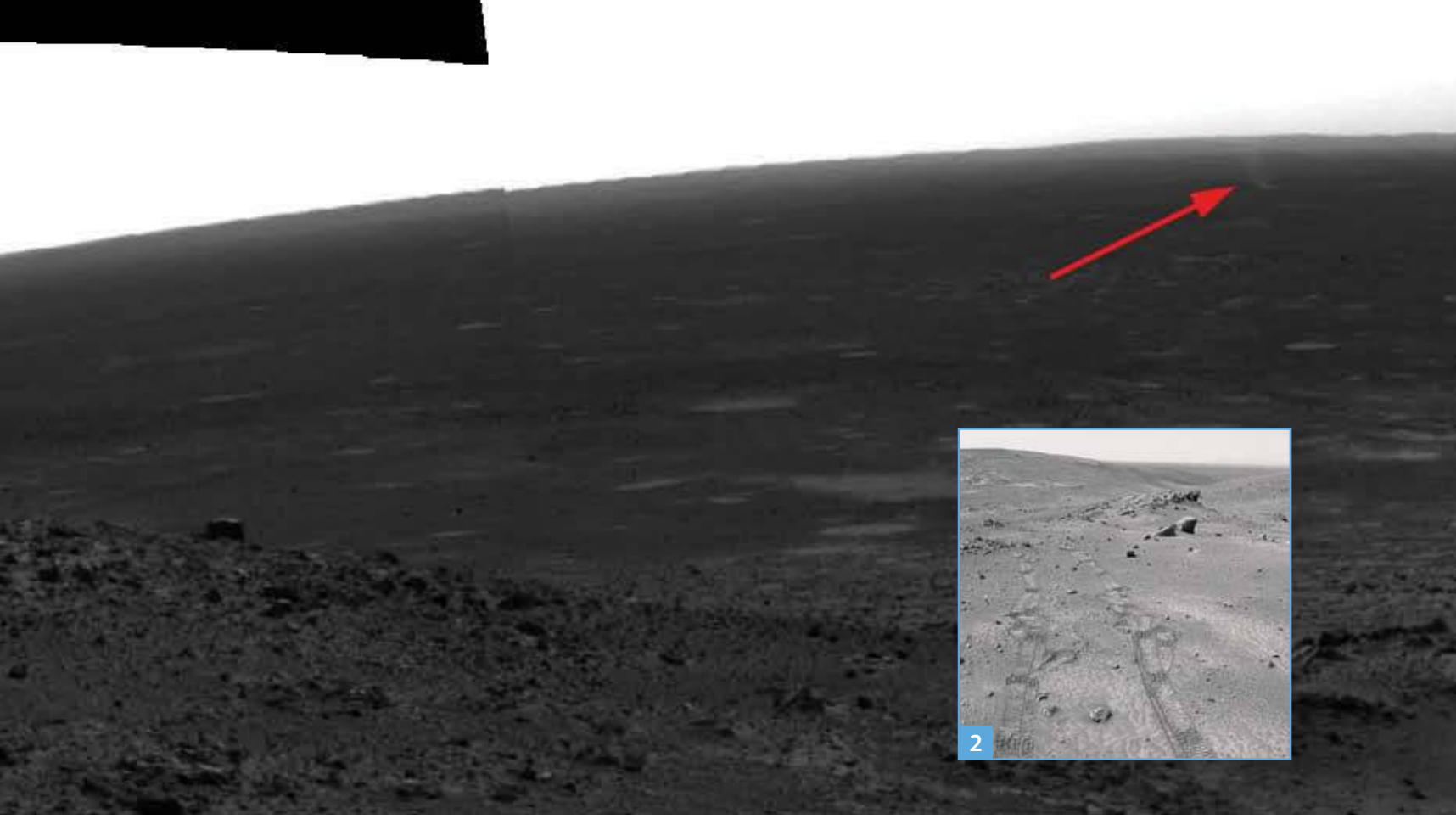
1 TWO DUST DEVILS (arrows) moving at 7 mph through Gusev Crater appeared about three-quarters of a mile from Spirit March 10, 2005 (sol 421). NASA/JPL

2 LARRY'S LOOKOUT may have formed from stacked and tilted layers of sediment when water flowed into Gusev Crater. Spirit's navigation camera took this image March 27, 2005 (sol 438). NASA/JPL

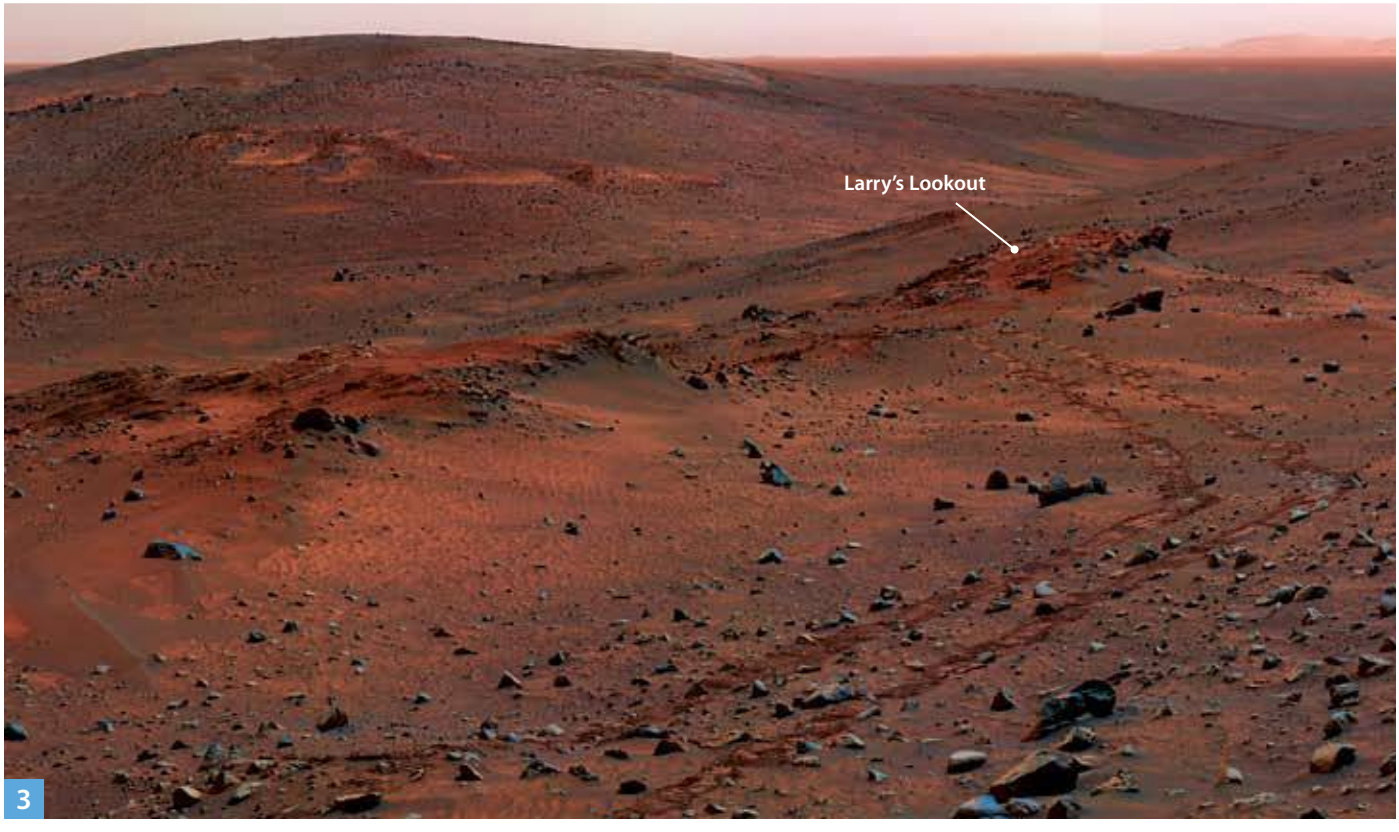
3 IN THE COLUMBIA HILLS, Spirit approached an outcrop named Methuselah April 13, 2005 (sol 454), when its panoramic camera took this image. The rover traveled from another outcrop called Larry's Lookout. To find it, follow the tracks back to the right. NASA/JPL/CORNELL

4 FULL POWER returned to Spirit after a "cleaning event," possibly by a martian dust devil. The left image shows dust accumulation on Spirit's panoramic camera's calibration target as of March 5, 2005 (sol 416). Ten days later, the target is much cleaner. NASA/JPL/CORNELL





2



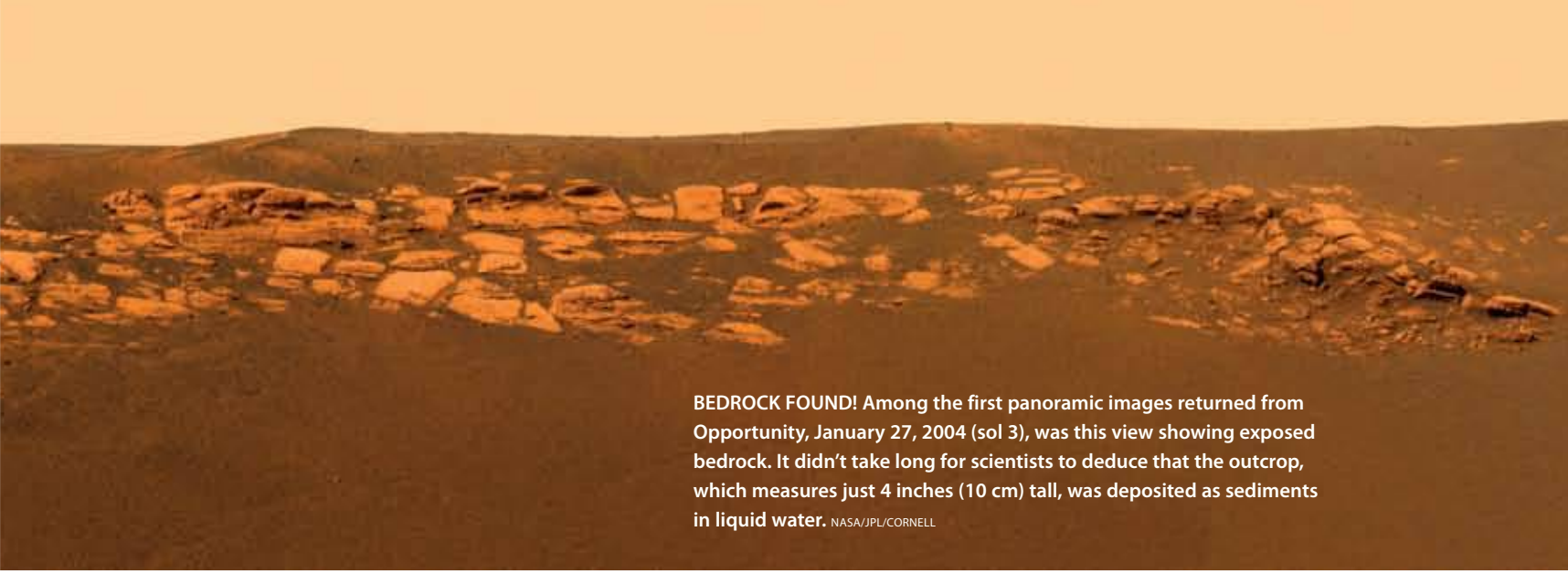
3

OPPORTUNITY ROVES MERIDIANI

Opportunity, the little rover

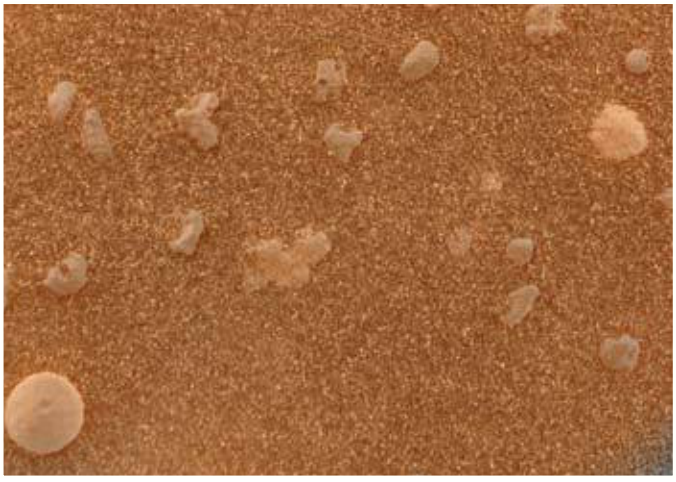
The Opportunity rover found evidence for wet, salty environments everywhere it looked

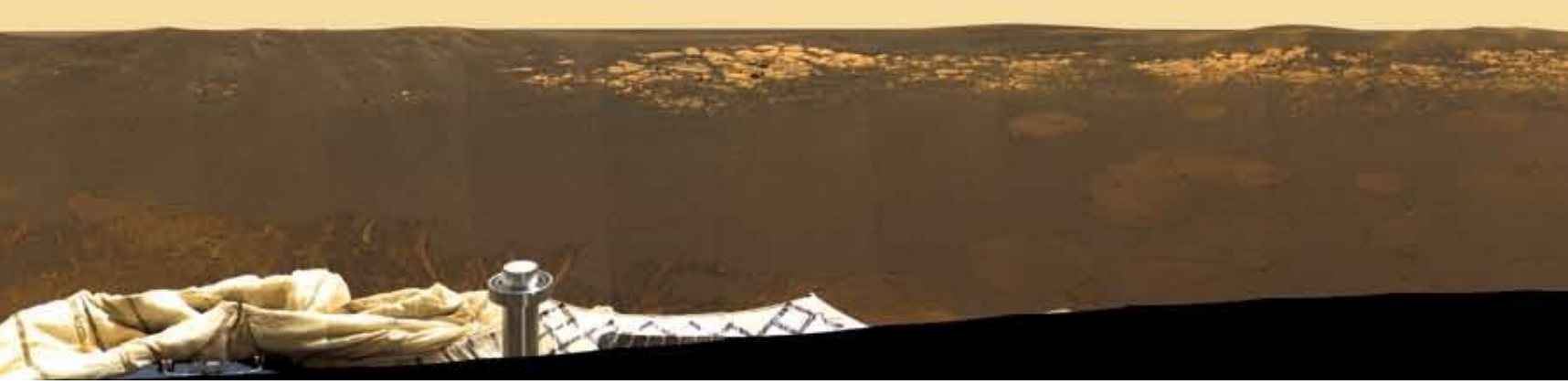
BY DAVID HANDY

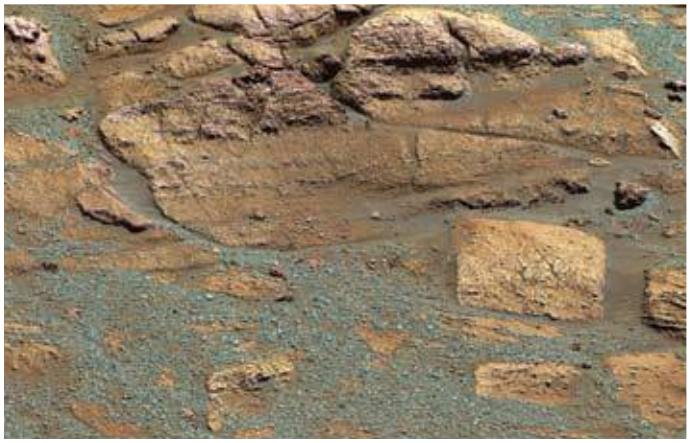


BEDROCK FOUND! Among the first panoramic images returned from Opportunity, January 27, 2004 (sol 3), was this view showing exposed bedrock. It didn't take long for scientists to deduce that the outcrop, which measures just 4 inches (10 cm) tall, was deposited as sediments in liquid water. NASA/JPL/CORNELL

PLANUM







▲THE EL CAPITAN REGION of the rock outcrop inside Eagle Crater offered another sterling site for detailed analysis. These images show El Capitan from two slightly different perspectives: The view at bottom was taken February 11, 2004 (sol 18), from the "Alpha" way station, while the top view shows the area February 12, 2004 (sol 19), from the "Bravo" way station. NASA/JPL/CORNELL

relentless roving, after lasting many multiples of its design lifetime. Opportunity has delivered more than anyone expected.

Not a bad performance for a golf-cart-size, six-wheel buggy that landed in a place some planetary scientists considered a long shot for turning up anything interesting. Meridiani Planum has turned out to be the most revealing part of Mars yet explored.

Opportunity has witnessed a geological bonanza since day one. While its sister rover, Spirit, wandered for months in a wilderness of volcanic basalt, Opportunity struck pay dirt instantly. Even its arrival was nothing short of miraculous.

Its chosen landing site is an almost featureless plain the size of Oklahoma — just the kind of hazard-free zone engineers always try to steer the science team toward. Of course, that tends to mean there's little of interest around.

But what made this plain special was a subtle signal, something picked up only through a spectrometer aboard the orbiting Mars Global Surveyor spacecraft. For some reason, Meridiani was broadcasting the presence of hematite, an iron-rich mineral that on Earth usually forms in water. Only two other smaller places showed this signature, and both were too hazardous for a landing.

Meridiani has little topographic variation. But Opportunity did something the launch team never could have accomplished if it had tried on purpose: The rover bounced right into the middle of a 65-foot-diameter (20 meter) crater and instantly came face-to-face with the first exposure of bedrock ever seen on Mars' surface.

Those first images, delivered within hours of the landing January 25, 2004, showed what look like towering cliffs of finely layered light rock. In fact, although they soon soared in importance, the exposures are tiny, closer to the height of a curbstone.

Besides the bedrock, there are some other strikingly different features at Opportunity's landing site. This clearly is a different part of Mars than that seen by the previous four landers: Viking 1, Viking 2, Mars Pathfinder, and Spirit. The soil is much darker, and, instead of boulders, it is strewn with what look like tiny beads, which mission scientists dubbed "blueberries."

These perfect spherules were enigmatic from the start. There are few ways to get such shapes: lava droplets that solidify in midair; impact-ejecta droplets shaped in much the same way; or something that forms in water, most likely as concretions built up slowly one layer at a time.

Determining the composition of the spheres became a priority. That's hard to do: The three spectrometers on the rover — the Alpha-Proton X-ray Spectrometer, the Mössbauer Spectrometer, and the mini-Thermal Emission Spectrometer — all have fields of view much larger than the tiny berries.

But the scientists got lucky. They found a natural depression in the rock where dozens of berries had collected — called the "blueberry bowl." By subtracting the spectrum of a patch of adjacent bare rock from that of the blueberry-littered spot, the scientists were left with the berry spectrum. And there it was: The blueberries are by far the richest source of hematite in the area.

That answered one big question about Meridiani, identifying the hematite repository seen from orbit. And it added another tantalizing bit of evidence toward the big question. It didn't prove the berries formed in water, but it pushed thinking in that direction.

▲ A PERFECT HOLE-IN-ONE — Opportunity landed smack in the middle of a 65-foot-wide (20 meter) crater called Eagle. This 360° panorama, taken February 1, 2004 (sol 8), shows what the martian rover's first home looked like. NASA/JPL/CORNELL

Opportunity spent about 2 months — the better part of its 90-day design lifetime — inside the crater of its arrival. (The crater was called Eagle to honor Apollo 11's lunar module, Eagle.)

And no wonder. As Opportunity studied practically every inch of the only bedrock exposure yet found on Mars — Spirit was still far from making its first such detection — it discovered one piece of evidence after another pointing toward water.

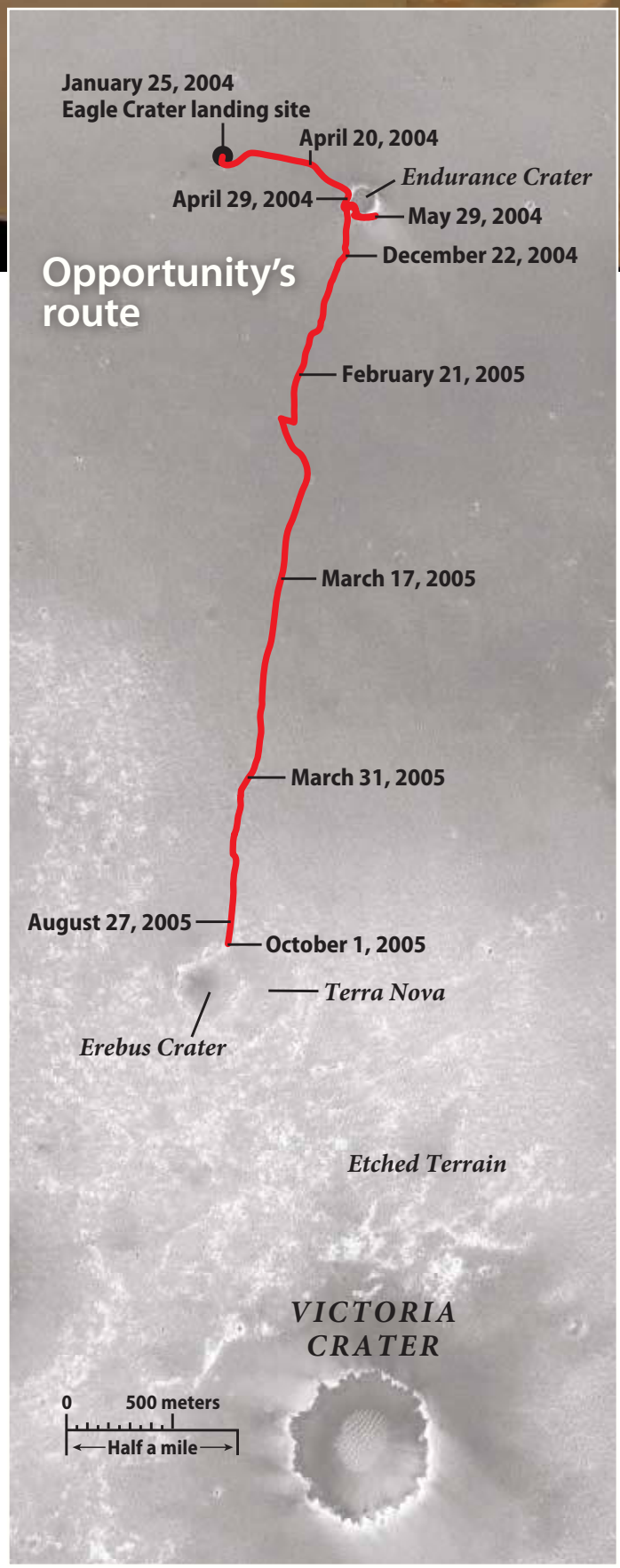
"Liquid water once drenched the surface," NASA chief scientist Ed Weiler exclaimed at a NASA press conference March 2, 2004. It was the first on-the-ground fulfillment of the agency's strategy to search for life by "following the water."

As Cornell University's Steven Squyres, the rover mission's lead scientist, summed up at the press conference, there was no single smoking gun that proved the presence of water. But added together, the independent lines of chemical, mineralogical, and morphological evidence make a nearly ironclad case.

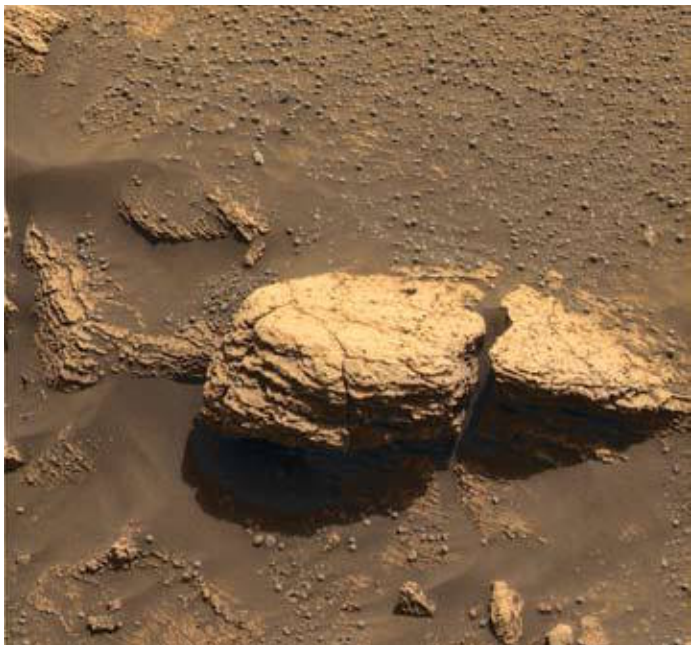
Opportunity's microscopic imager revealed cavities in some of the rock that match the shapes of certain salt crystals, showing the rock formed around the crystals, which later dissolved in water. The rover's spectrometers found high levels of sulfur, suggesting the rock formed in salt water. The spectrometers also detected the mineral jarosite. Scientists know of no other way to form jarosite than by deposition in water — especially highly acidic water, which remains stable at much lower temperatures than neutral water.

All the evidence showed water, but it still might have been water in the ground, saturating the soil. Had water ever stood on the surface? After all, many scientists think the features resembling riverbeds, lakebeds, and perhaps even beds of ancient seas or oceans seen by previous spacecraft attest to long-ago surface water.

The proof of surface water took only 2 more weeks to find. And again, the evidence came from the bedrock exposures within Eagle Crater. Opportunity saw distinctive, curved shapes called festoons in the layers of sand-size particles making up the rock; festoons form only by the action of waves in a shallow body of water.



▶ IT'S BEEN A LONG ROAD for Opportunity, from its landing in Eagle Crater in January 2004, across some tricky sand dunes in Meridiani Planum, to the rim of Erebus Crater. *ASTRONOMY:* ROEN KELLY



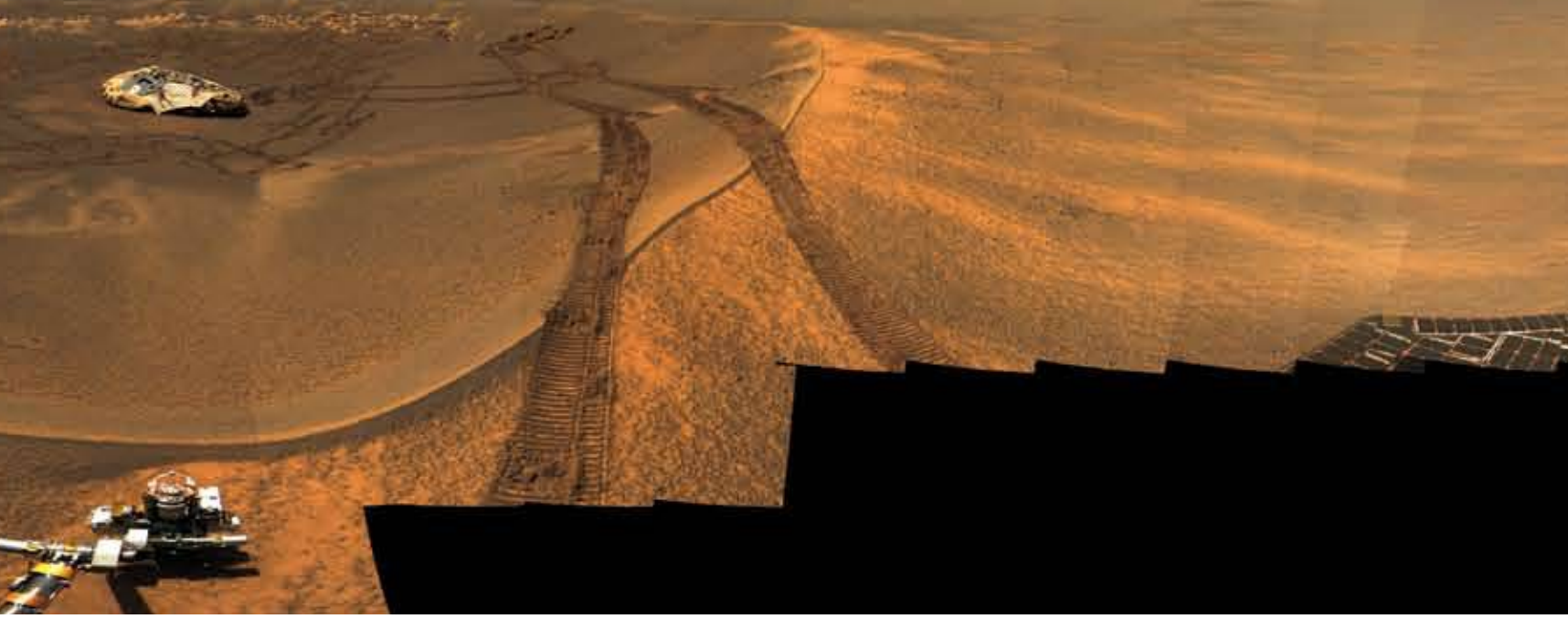
As Squyres summarized, the shapes of those layers showed Opportunity had its wheels parked on "the shoreline of a salty sea."

The answer was in hand — Mars indeed had been wet. Mission accomplished. Some might be tempted to ask, why go on?

Well, there was plenty more to do. At this point, however, it was time to leave the nest. Eagle had revealed its secrets. But if this area once had been wet, how long had the episode lasted? Was it a one-time occurrence, or sustained over millennia, or a series of recurring episodes? The only way to find out would be to locate

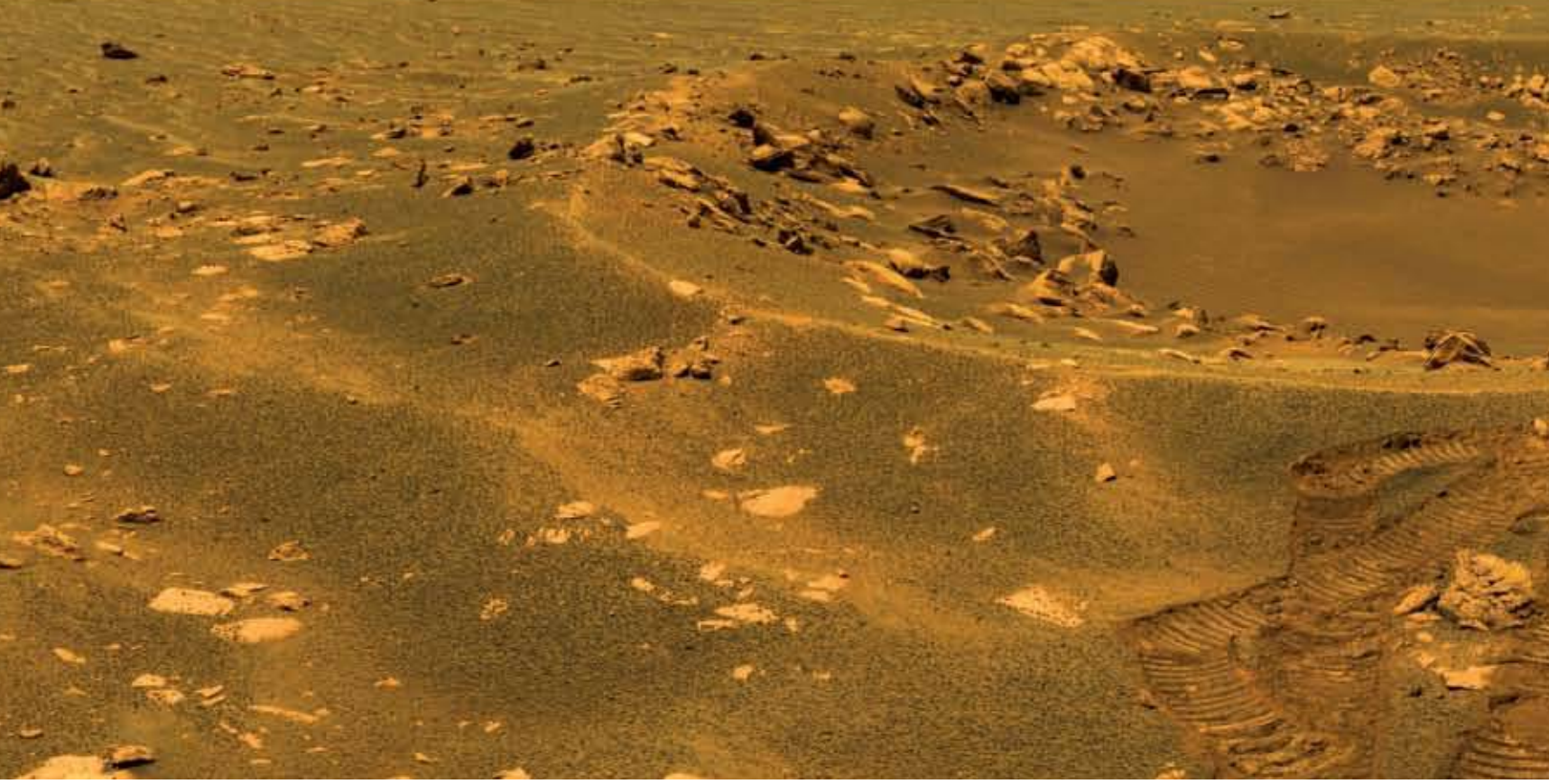
◀**STONE MOUNTAIN doesn't exactly reach for the sky. Instead, it consists of just this 6-inch-tall part of the rock outcrop in Eagle Crater. Stone Mountain protrudes farther from the bedrock than most other regions, so it was a prime target for Opportunity. The rover snapped this image February 9, 2004 (sol 16).** NASA/JPL/CORNELL

▼**OPPORTUNITY SITS IN EAGLE CRATER, its first home on the martian surface. The rover and its retracted airbags are seen at the bottom of the image, taken January 25, 2004 (sol 1). The crater's rim lies approximately 33 feet (10 meters) away.** NASA/JPL/CORNELL

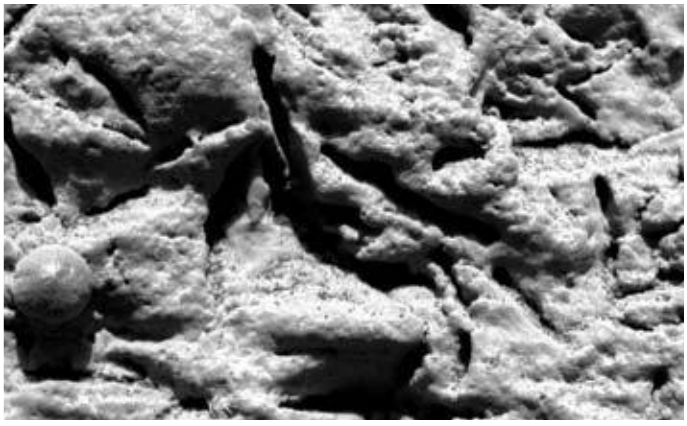


▲ **OPPORTUNITY CLIMBS OUT OF EAGLE CRATER, looking back on where it spent its first 2 months on Mars. The rover's tracks chart its explorations from the landing platform at center to the expose bed rock on the crater s far side. Opportunity took this image between March 23 and 25, 2004 (sols 58 and 60).** NASA/JPL/CORNELL

▼ **OPPORTUNITY'S LANDING PLATFORM sits in Eagle Crater, where it came to rest 24 sols before this image was taken (February 17, 2004). After touchdown, mission controllers renamed the lander the Challenger Memorial Station, in honor of the astronauts who died in the space-shuttle disaster in January 1986.** NASA/JPL/CORNELL



▲ **FOUR-INCH-TALL BOUNCE ROCK was the largest rock as far as Opportunity's eyes could see while the rover remained inside Eagle Crater. The rock got its nickname because the airbag-protected rover struck it as it was bouncing to a stop during landing. Dust covers the top part of the rock, which may have broken when the airbags hit it. This image was taken March 1, 2004 (sol 36).** NASA/JPL/CORNELL



▲ **A WAYSIDE ON THE JOURNEY to Endurance Crater, the rock-strewn impact crater dubbed Fram spans about 26 feet (8 meters). Opportunity paused here April 23, 2004 (sol 88), before continuing eastward toward Endurance.** NASA/ASU/CORNELL

other expanses of exposed bedrock that revealed more than the few inches exposed inside Eagle.

There was a tempting target out there, although its distance of 0.6 mile (1 kilometer) seemed a bit daunting for a rover designed to be a success if it could cover half that distance. The team decided to go for it: a 625-foot-wide (190 meter) crater they called Endurance, which appeared to have bedrock exposures of many yards.

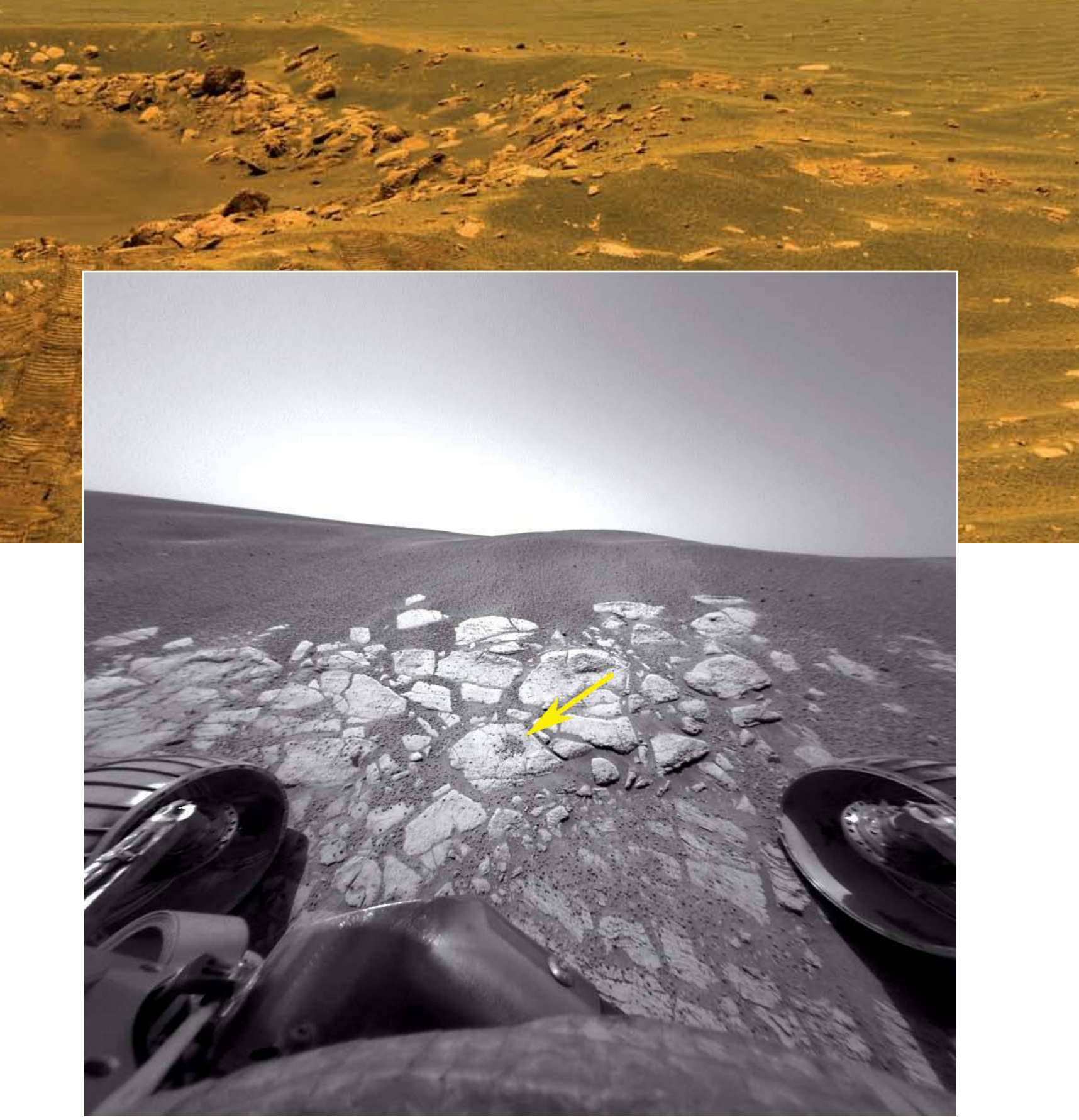
Opportunity reached the rim of Endurance in May 2004 and spent the next few weeks traversing up and down the rim. The rover took detailed pictures of what the team had hoped for — wide, deep exposures of bedrock. All of them seemed to show signs of fine, complex layering.

And everywhere, as always at Meridiani, were blueberries.

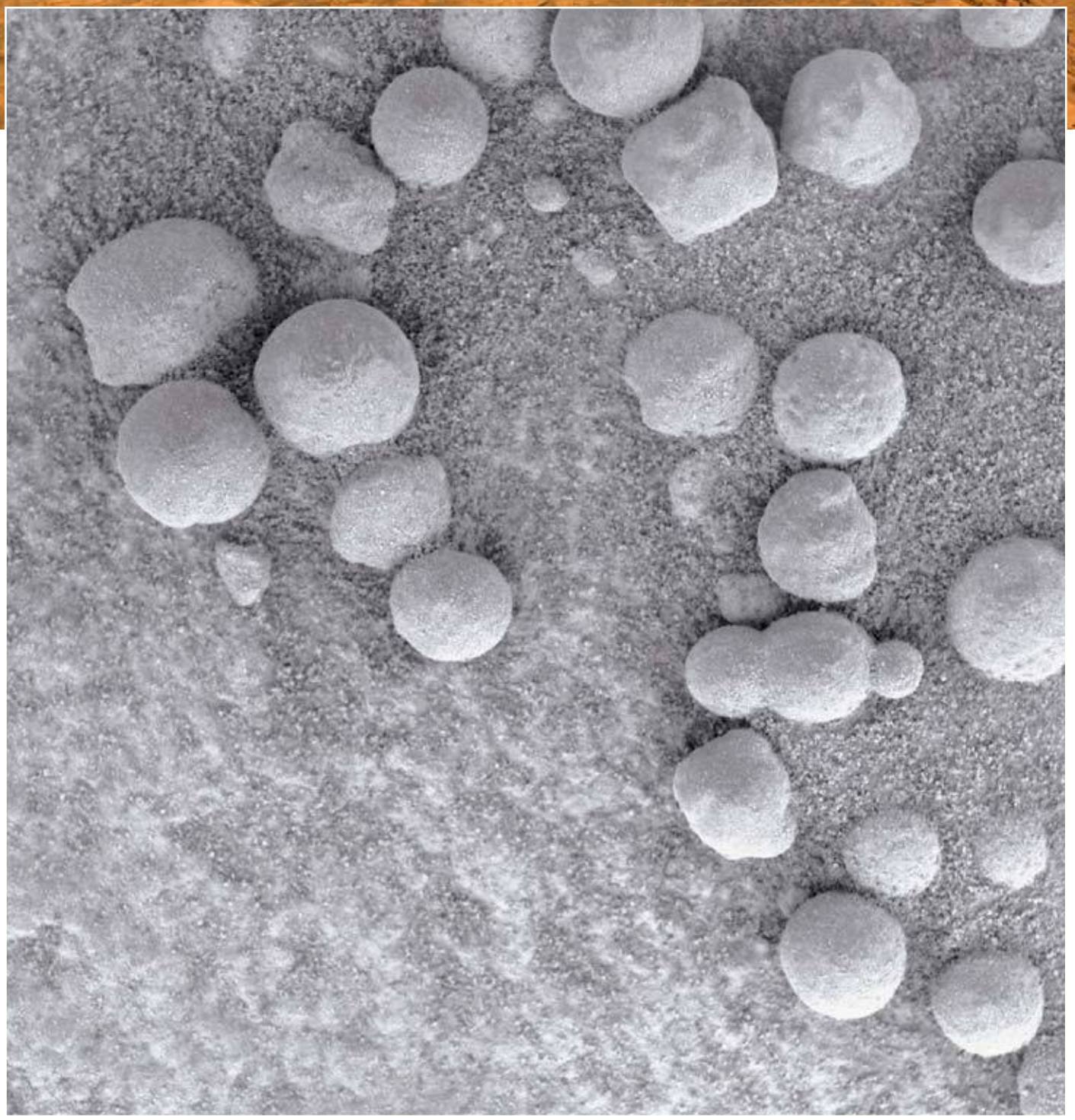
Roving steep slopes on a surface littered with loose, polished spheres turns out to be tricky. It took a long time for the rover team to decide to go over the edge and into the crater itself. And sure

(continued on page 89)

◀ **WAFER-THIN LAYERS only 0.04-inch thick (1 mm) run horizontally through the lower portion of this microscopic image, taken February 23, 2004 (sol 29), at the outcrop region known as El Capitan. The blueberry at left does not disturb the layers, which suggests the spheres are concretions that form in wet sediments and are not solidified droplets of impact ejecta or lava.** NASA/JPL/CORNELL/USGS

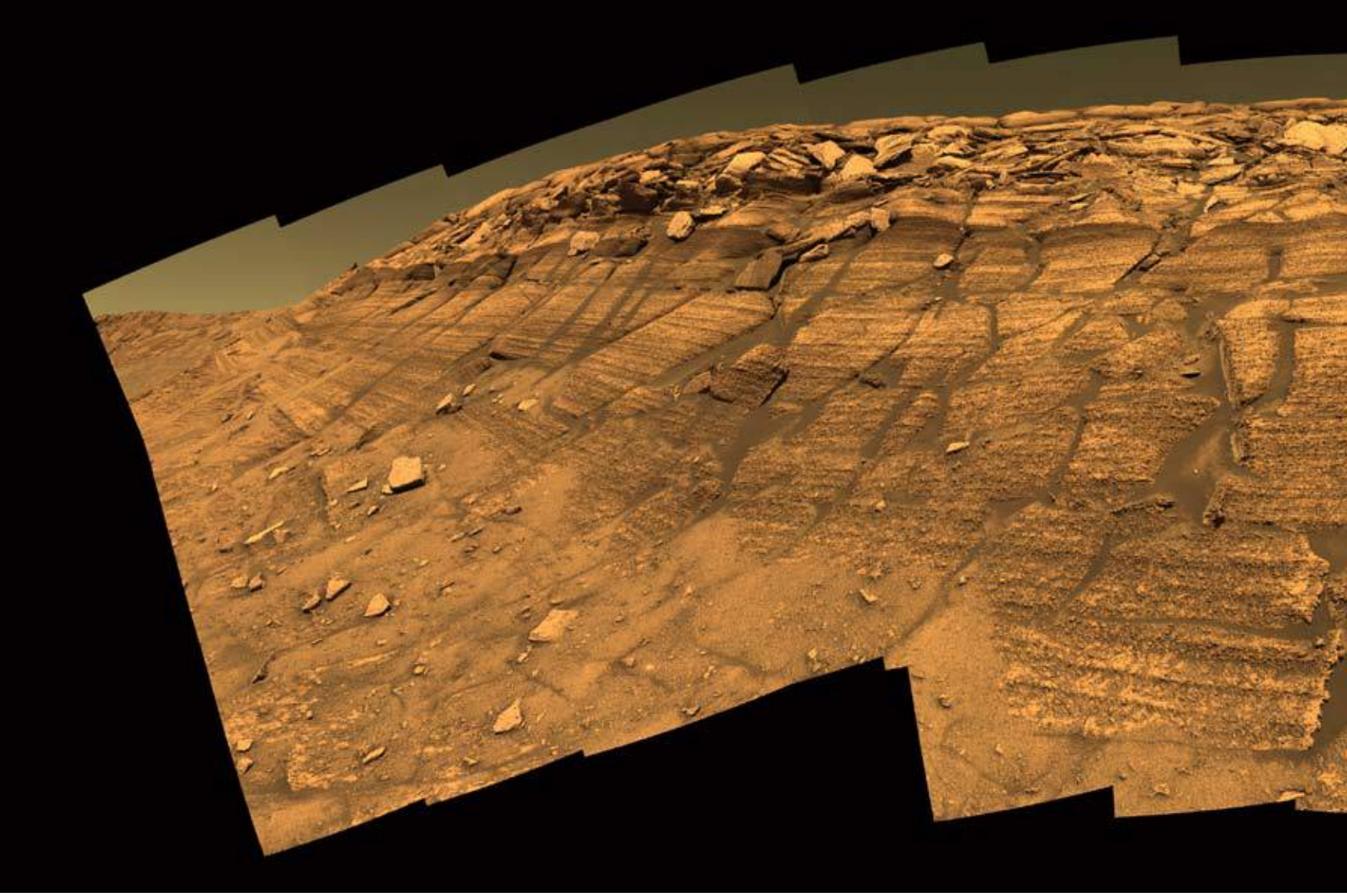


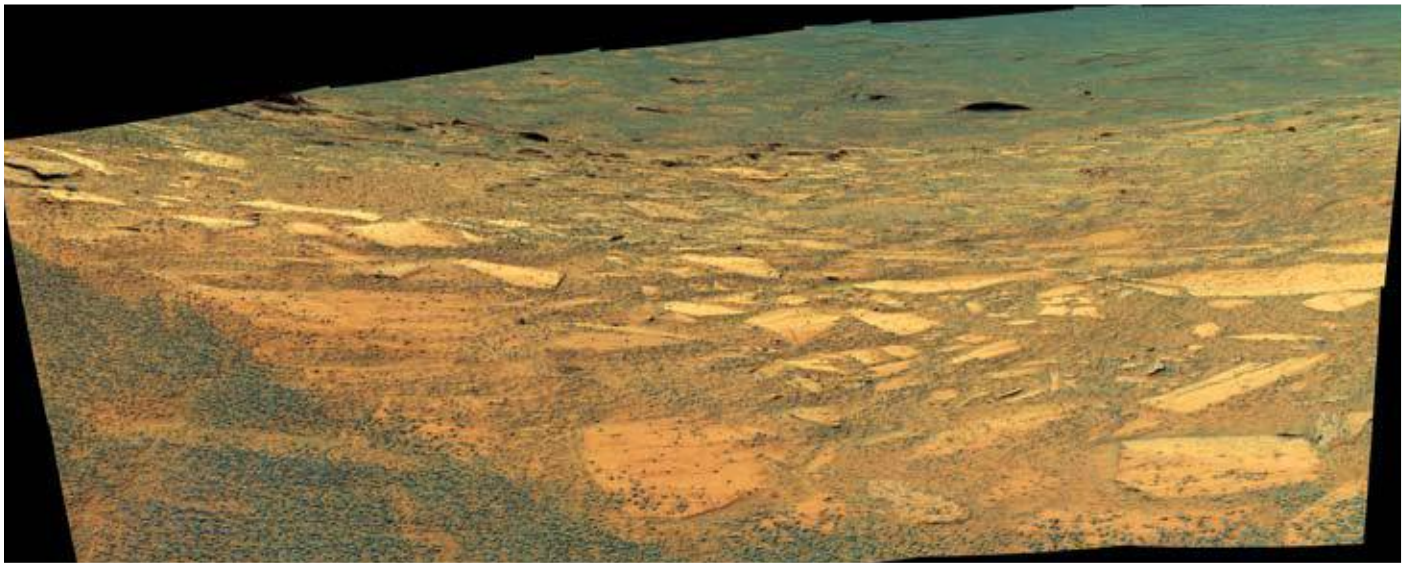
▲ **THE "BLUEBERRY BOWL" (arrow) was just what mission scientists were looking for: a collection of blueberries dense enough for Opportunity's instruments to get a good spectrum. Careful analysis showed the berries to be rich in hematite, an iron-rich mineral typically formed in water. The rover's front hazard-avoidance camera took this image March 10, 2004 (sol 45).** NASA/JPL



"Liquid water once drenched the surface."

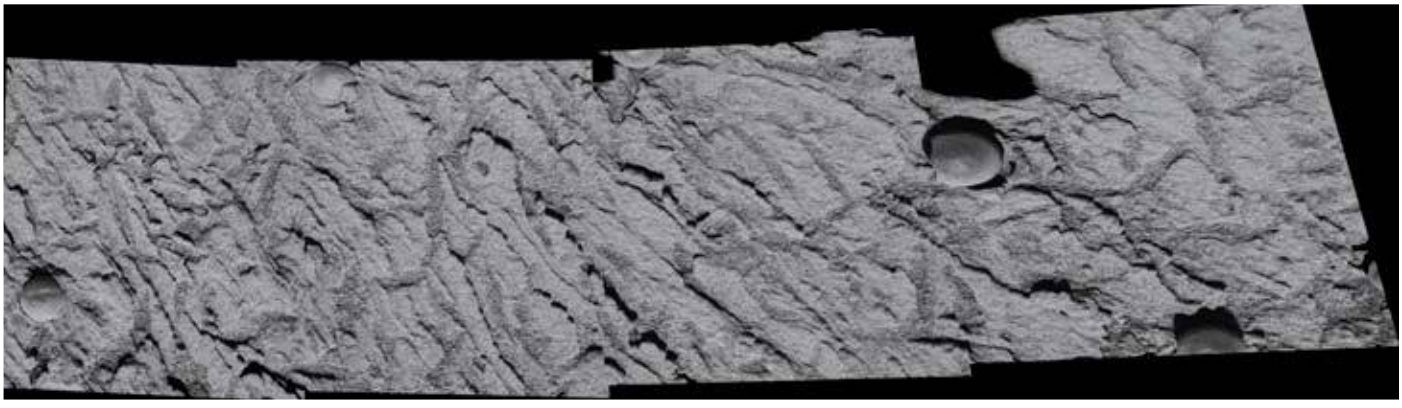
— Ed Weiler





▲ **A BLUEBERRY-STREWN SLOPE greeted Opportunity when it reached the edge of Endurance Crater. The gradual incline contains an exposed layer of dark rock that wraps around the crater's upper section. The rover captured this false-color mosaic June 6, 2004 (sol 131), combining images taken from 10 separate locations and through 3 different filters.** NASA/JPL/CORNELL

BURNS CLIFF forms Endurance's southeastern wall. Taken between November 13 and 20, 2004 (sols 287 and 294), this wide-angle mosaic makes the cliff appear to bulge inward. NASA/JPL/CORNELL



▲ **TINY RIPPLE PATTERNS** seen on the southeastern part of Endurance Crater's rim hint at the water-rich history of Meridiani Planum. Planetary scientists think the ripples and other fine textures seen here further prove the crater's sulfate-rich outcrops were laid down in water. This mosaic combines nearly 150 images taken by Opportunity's microscopic imager. NASA/JPL/CORNELL/USGS

(continued from page 84)

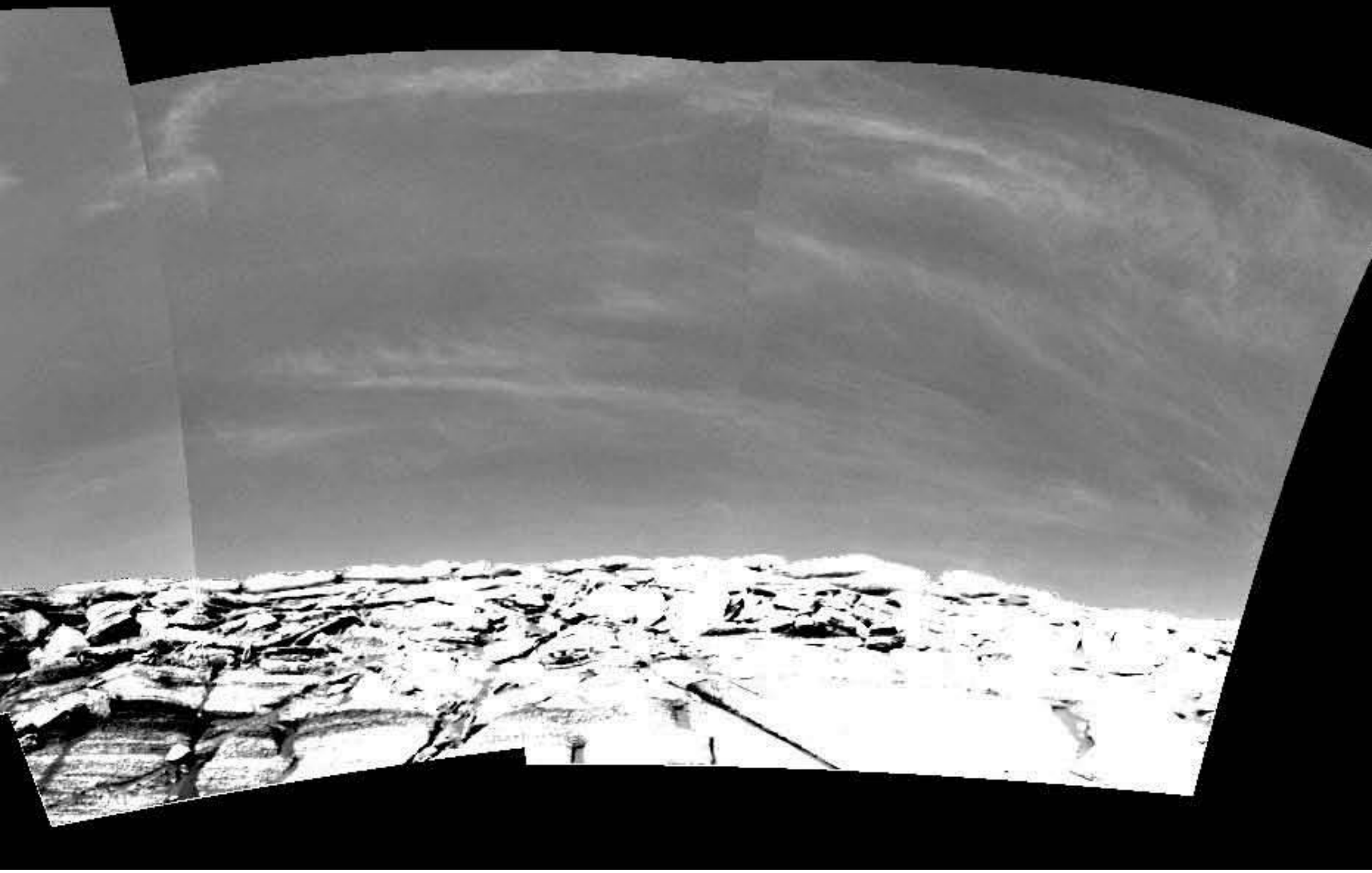
enough, some parts of the slope proved difficult to manage. Scientists abandoned attempts to reach the flat bottom of the crater — to sample its distinctive dunes — when Opportunity's wheels started slipping too much. The team also ditched an attempt to exit the crater by way of the steepest exposure, dubbed Burns Cliff.

But months of successful exploration inside Endurance, including the use of the rover's rock abrasion tool to probe beneath layer

▲ **RAT HOLES mark the spots where Opportunity's rock abrasion tool (RAT) ground targets into three separate layers on the slope of Endurance Crater. The top circle penetrates 0.18 inch (4.5 mm) into the rock, the middle one 0.17 inch (4.3 mm), and the bottom one 0.12 inch (3.0 mm). The rover dug these holes between June 18 and 23, 2004 (sols 143 and 148).** NASA/JPL/CORNELL

▲ **SAND DUNES ACCUMULATE at the bottom of Endurance Crater, creating a dramatic tapestry in this false-color image. The tendrils, which extend from the main dune field toward the rover, are less than 3.3 feet (1 m) tall. The crests have collected more dust than the flanks and the flat areas between them, which appear "blue" thanks to the presence of hematite-rich blueberries.** NASA/JPL/CORNELL

after layer of surface rock all the way down the bedrock exposure, gave just the kind of results the team had hoped for. While some scientists think certain layers in the exposure's middle might have been deposited by wind, there is little question most of the rock, including both the highest and lowest layers, formed in water.



▲ WISPY CLOUDS form near the martian equator when the planet lies farthest from the Sun, during the southern hemisphere's late autumn and winter. At this time of year, temperatures drop and moisture levels rise, creating the conditions for large-scale clouds much like cirrus clouds on Earth. The rover captured this scene November 16, 2004 (sol 290). NASA/JPL

Mars was a wet place, at least around Meridiani in the early days of the solar system. And it stayed that way for quite a spell, as Opportunity keeps documenting in ever-greater detail. Determining just how long it remained wet, however, is a tricky matter of interpretation and likely to remain contentious. Layer after layer, it's the same stuff: sulfur-rich rocks laid down in shallow water and riddled with hematite concretions that formed later in the saturated sediments.

After leaving Endurance, Opportunity proceeded to take a close look at its own jettisoned heat shield. More a matter of interest to mission engineers than planetary scientists, the impact site held lessons for everyone.

Close-up images of the shield's partially burned protective layer will help in the design of future planetary-probe heat shields. And the patch of ground where the shield struck is the first experimental impact site on another world ever studied in detail.

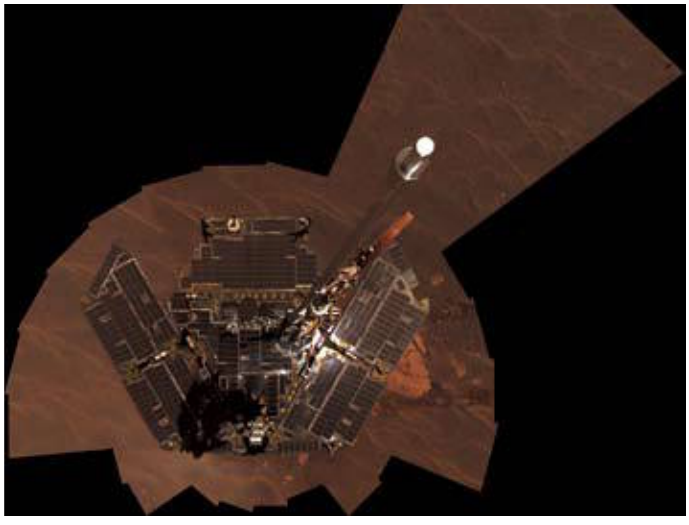
▲ AN ODD, LUMPY ROCK (the big one right of center) sits on the lower slopes of Endurance Crater. Named Wopmay, this rock and several others dotting Endurance's floor probably got their lumps when they cracked, most likely after being exposed to water that then dried up. Opportunity's panoramic camera took this image October 4, 2004 (sol 248). NASA/JPL/CORNELL

Some scientists hoped the shield might have excavated a nice trench, but it turned out to be the mark of a flat-side-down belly flop that compacted the ground only an inch or two. It seems this ancient seabed is hard stuff.

And amazingly, standing right next to the heat shield was the first meteorite ever found on another world. The foreign rock appears full of cavities and it revealed its nickel-iron composition to the rover's spectrometers.

Meridiani is so flat and rock-free that this could turn out to be the first meteorite of many. Like Antarctica and the desert of Western Australia, this may be a place where any rock that sticks up has a compelling story to tell.

▼**AFTER NEARLY A YEAR ON THE SURFACE, Opportunity was still going strong. This self-portrait, taken with the panoramic camera December 19 and 20, 2004 (sols 322 and 323), shows the rover minus the mast on which the camera is mounted. The solar panels appear remarkably clean after so long on the dusty planet.** NASA/JPL/CORNELL



▲**THE HEAT SHIELD'S IMPACT dented Mars' surface and scattered debris around the site. Sunlight glints off a layer of metallic insulation in the large piece at left, which stands about 4.3 feet (1.3 m) tall and 43 feet (13 m) away. Although the impact gouged out this 9.2-foot-wide (2.8 m) crater, it dug down only 2 to 4 inches (5 to 10 centimeters). Opportunity snapped this photo December 28, 2004 (sol 330).** NASA/JPL/CORNELL

After it left the heat shield, Opportunity's targets became much longer-range and more ambitious. It struck off toward Victoria Crater, which is 6 times bigger than Endurance. Planetary scientists hope Victoria will reveal even deeper exposures of bedrock than Endurance.

But Victoria lies more than 3 miles (5 km) from the landing site — a long trek, especially because it sits on the other side of a wide swath of "Etched Terrain," a mottled surface whose nature remains a mystery to scientists. It may turn out to be impassably rough, Squyres concedes. Or it might just be a region of low-relief surface shading and offer easy driving.

Whatever it is, it will be something new — another fresh vista for a rover whose travels have revealed a succession of scenes, each unlike anything previously encountered on Mars.

Maybe the Etched Terrain will provide more than a novel view. Maybe it will help solve the remaining puzzle of just what this strange region called Meridiani used to be, back in the relatively wet early days of Mars. If this was a shallow, salty sea, just how much territory did it cover?

Tim Parker, a geologist at NASA's Jet Propulsion Laboratory in Pasadena, California, has long thought there are clear signs of an answer to that question. The signs just keep getting stronger — but still not quite strong enough to win over skeptics.

Parker thinks Meridiani was a shallow region near the edge of a large ocean, which may have covered much of Mars' flat, smooth northern plains. If Meridiani Planum indeed was a shallow sea, as

most scientists now agree, higher ground to the south probably contained it. But what held back the water to the north? There, the slope drops slowly and relentlessly.

Perhaps an ancient margin existed to the north, a shoreline now completely eroded away that once enclosed a basin the size of a small sea. If so, it left no traces, and its removal would have been a selective process because the rest of the vast, fl t plain seems to have been unaffected.

Parker and several other scientists, including James W. Head of Brown University, argue instead that the coincidence of topographic levels and apparent shoreline features suggests a vast ocean once covered the northern plains. In that case, Meridiani would have been a mostly submerged platform near the ocean's edge — something like the Bahamas, Parker suggests.

If so, the formation process must have been different than the way such carbonate platforms build up in terrestrial oceans. The chemistry of the highly acidic and salty waters, as revealed by Opportunity's instruments, is so exotic that it will take a while for theorists to figure out how geophy?ical processes operated there.

Whatever the extent and duration of that early wet phase of martian history may have been, Opportunity's data have dine more than just clarify and prove early wetness — they also have shown how dramatically things changed there long ago. The vast rippled plain seems to have remained virtually unaltered since drying up within the planet's first billio ?years. The only apparent change in this region has been the unimaginably slow removal of the finest dust particles by millennia of winds. Matt Golombek, chief scientist of the Mars Pathfinder mission and a member of the current rover science team, says calculations based on the soil images t?ken by Opportunity suggest an ove all rate of wind removal that translates to one atom per year across the planet.

Such calculations are "a blunt indicator of the climate," he says, but they indicate that "it's possible nothing has happened in 3 billion years except 12 centimeters of deflation."

▲ AN IRON METEORITE sits on the martian surface not far from Opportunity's heat shield. The rover discovered the pitted, basketball-size object — the first meteorite ever seen on another planet — and used spectrometers to confirm the rock's nickel-iron composition. The rover took this image January 6, 2005 (sol 339). NASA/JPL/CORNELL

Or perhaps it has been more complicated than that. Episodes of deposition and removal could mask some of the variations that took place in between. One of the lessons of these far-ranging rovers is just how little we still know, and how vast are the unexplored regions of Mars that remain.

Perhaps Opportunity's continuing trek finally will reach layers of rock that reveal enough of the past to clear up the mysteries, one way or the other. Or maybe not.

Maybe the puzzles of the past martian climate will remain unsolved much longer, perhaps even until the arrival of the first human footprints. Footprints that someday may join the sharply etched wheelprints of the rover that first ope?ed up the exotic views of Meridiani to human eyes.

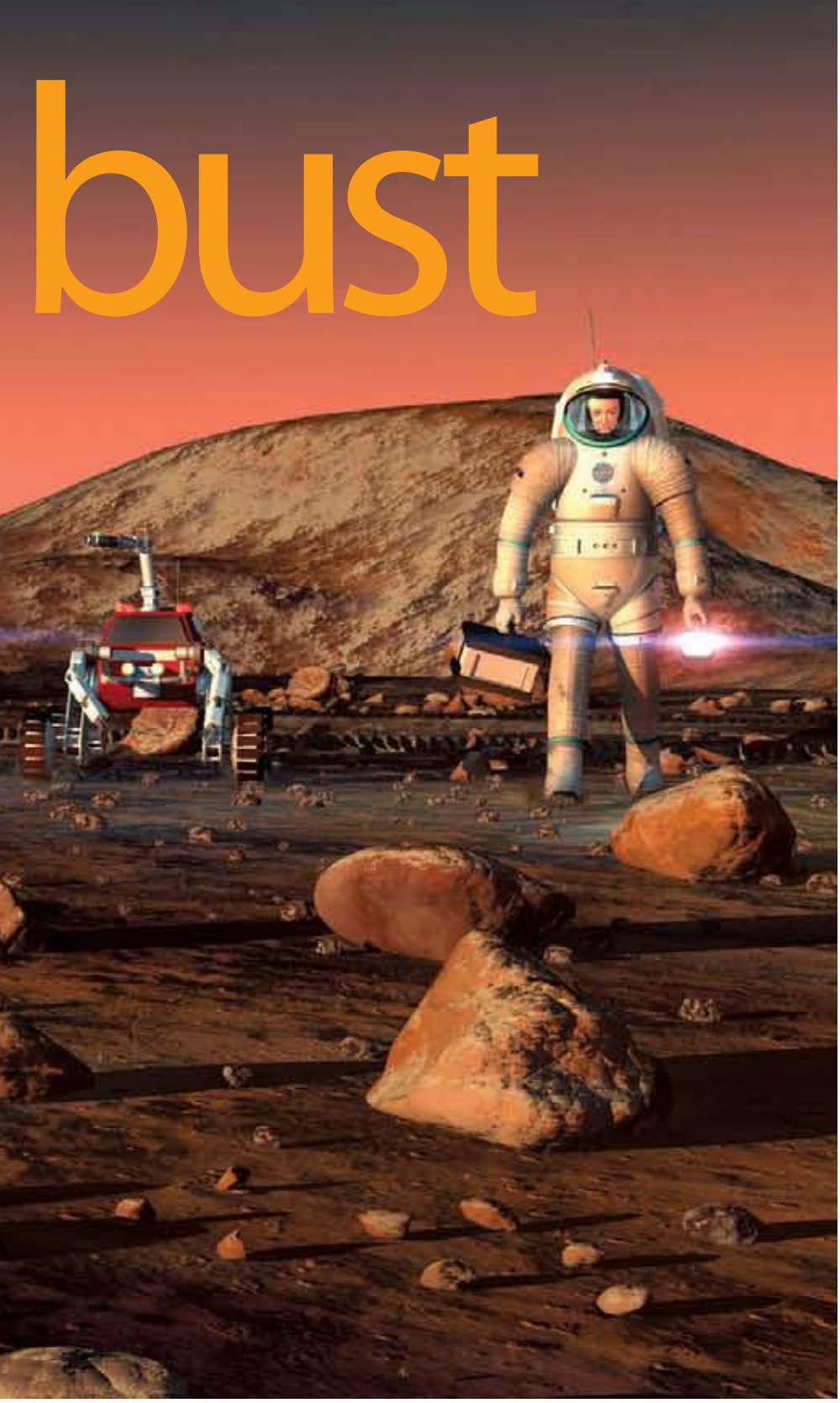
David Chandler *is a freelance writer who formerly covered the science beat for the* Boston Globe, *the Bay State's largest newspaper.*

Mars or

The fantastic success of the Mars Exploration Rovers Spirit and Opportunity — both now approaching 2 Earth years on the Red Planet — comes from the latest step in an ambitious program of orbiters and landers. They will lead to the ?rst human flights to Mars, around 2030, according to NASA.

At this point, the target date is only a target — reality and hard-won space-flight experience suggest it could slip backward, perhaps by as much as a decade.

Yet building on the rovers' triumphs, civilian space scientists and engineers are busy designing an extensive Mars exploration



◀ **MARS' POLAR REGIONS** are targeted sites for human exploration; detecting traces of life is a possibility in these wate covered features. NASA/JOHN FRASSANITO & ASSOCIATES

program. It is structured around new orbiter missions and lande s that wil blaze the trail for humans under P esident Bush's Vision for Space Exploration, also known as the Moon-to-Mars initiative. Add to these missions-in-the-works the prospect — s ill on the drawing boards — of a Mars samp e-return mission in the 2010s, and you have a new recipe for unlocking the Red Planet's secrets.

In February 2005, NAS announced a $723.1 million budmet for Mars exploration for fiscal year 2006, rising every year to $1.26 billion in 2010. If fully funded by Congres , ?his will be the largest robotic solar-system exploration program in NASA history.

NASA has designed the Mars Exploration Program around a series of highly focused science and technology objectives. The scientific goals are ambitious but straightforward: Determine if life ever arose on Mars; characterize the martian climate; map the planet's geology; identify water-related features; and prepare the way for human exploration missions. This marks the first time since the Apollo Moon-landing era of the 1960s that the space agency has directly linked a robotic-program objective with manned exploration missions.

To create the means to reach these goals, NASA is developing a series of advanced technologies. Spirit and Opportunity underscore the importance of mobility on Mars while also demonstrating their limitations. Running entirely on solar power makes life difficult for the rovers; sunlight on Mars has only half the strength as on Earth. Worse, the ever-present dust coats solar panels, further reducing their energy output as time goes on. And mission planners can't count on dust devils conveniently blowing a lander clean, as happened with Spirit in March 2005.

Skimpy power reserves forced both rovers into "hibernation" during the depths of the martian winter, and while no instrument failed due to cold, this may have been due mostly to luck. The instrument payload was kept simplistic to conserve power.

Finally, even if the rovers traveled much farther than their builders expected, they still covered only a tiny portion of the planet — and every Mars scientist wants to see as much as possible.

In addressing these issues, NASA plans on equipping future missions with systems that include new kinds of propulsion, extra power, faster telecommunications, better avionics, and improved software. For sample-return missions, and ones to survey specific sites, add to this list new entry, descent, and landing technologies so heavier, and more capable, spacecraft can set down safely.

Mission designers want systems that would give rovers more autonomous mobility and would shield spacecraft better for extended surface stays. They also desire more-robust science instruments. Planners seek to develop new types of surface instruments that could function for years after their initial missions, serving as semi-permanent surface laboratory stations.

A sample-return mission will need technology that can select and collect rock, soil, and atmospheric samples and pack them into a launch vehicle/reentry capsule for the trip to Earth.

Despite the growing sophistication of future Mars spacecraft, they will still need to be sterilized. All Mars-research programs are guided by internationally agreed-upon protocols for planetary protection. The protocols involve technology for cleaning and sterilizing a lander and its components. No one wants to carry Earth bugs to Mars — or contaminate Earth with martian ones.

The first element of the exploration program is the ***Mars Reconnaissance Orbiter (MRO)***, which launched August 12, 2005. After a 7-month cruise, the spacecraft will reach the Red Planet in March 2006.

MRO will fire its rocket engine and enter a highly elliptical orbit around Mars. At its lowest point — 180 miles (300 kilometers) above the surface — the spacecraft will brush through the outer martian atmosphere. During a 6-month-long process called aero-braking, MRO will use the feeble drag exerted by the atmosphere to make its orbit more circular. The final orbit for science operations, achieved through aero-drag and thruster firings, will be about 280 miles (450 km) high.

▲ **FOLLOWING** a 7-month trip, MRO will aerobrake into a circular (from an elliptical) orbit to perform the mission's science objectives. NASA/JPL

▲ **MRO WILL USE RADAR** to look for subsurface water and ice. This will identify locations to explore in future missions. NASA/JPL

Once operational, MRO will search for traces of water from orbit using the most advanced cameras ever to fly aboard a planetary probe. Imaging objects on the surface as small as a beachball, the HiRISE (High Resolution Imaging Science Experiment) camera will identify and catalog rocks that could pose hazards to future landers. An imaging spectrometer, CRISM (Compact Reconnaissance Imaging Spectrometer for Mars), will focus on smaller targets than previous orbiting spectrometers. With a resolution of 60 feet (18 meters), the instrument breaks visible and near-infrared light from the surface into hundreds of "colors" to identify minerals, especially

▲MARS' POLAR ICE CAPS are targets of instruments aboard MRO and should help astronomers learn about water on the Red Planet. NASA/JPL

those likely formed in the presence of water. A ground-penetrating radar, SHARAD (Shallow Subsurface Radar), will detect liquid or frozen water in the soil's top few hundred feet. Other instruments will monitor the planet's cloudiness, dust storms, and variations in atmospheric temperature and water vapor.

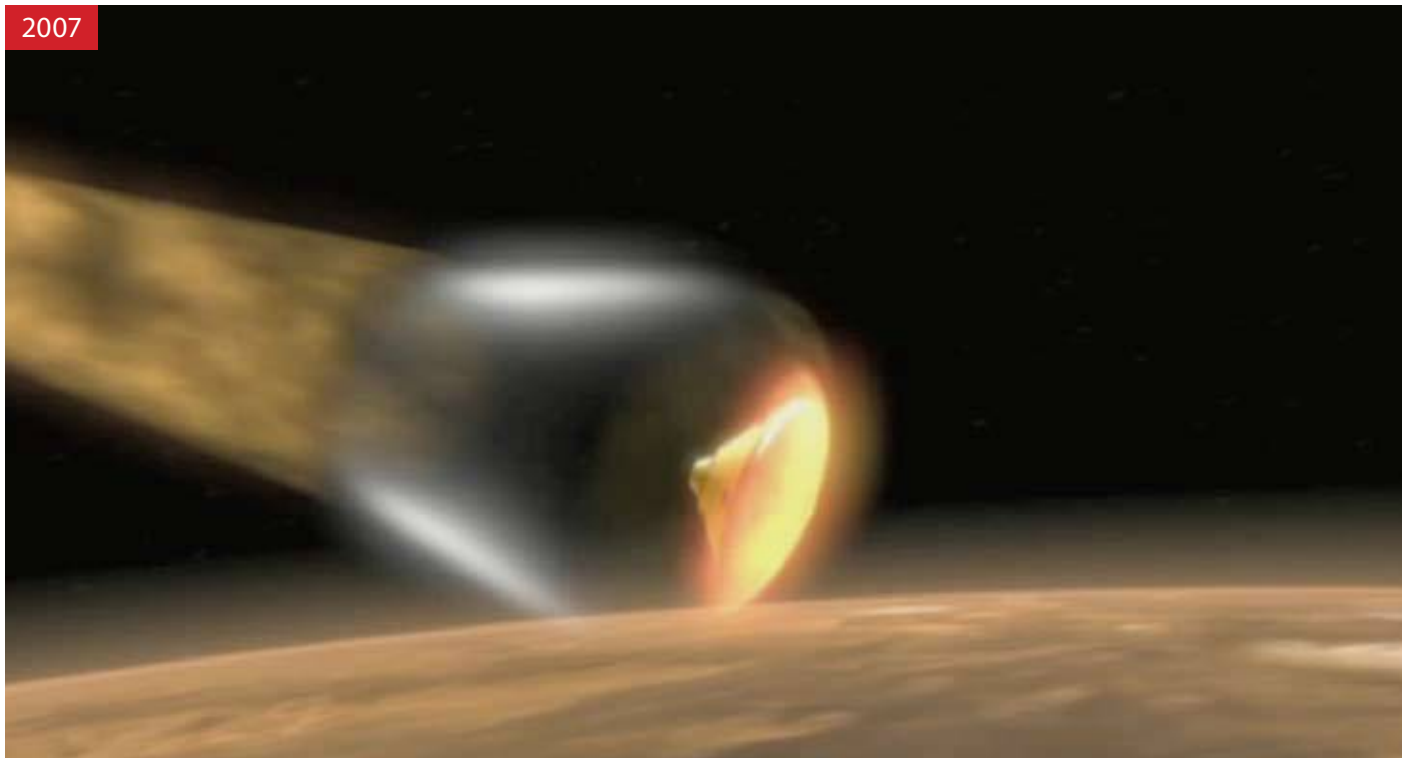
Looking further into the future, Mars Reconnaissance Orbiter's mission includes a test of a Ka-band radio system at 32 gigahertz (some police radars use a similar frequency). This radio will be the first system used in establishing an "interplanetary Internet" and communications bridge to Earth for spacecraft on the martian surface. Commands from Earth could be forwarded to a lander, or its data could be returned to Earth via the link. It would be like giving Mars landers and rovers a broadband Internet connection and letting each use it for 5 minutes twice a day.

MRO's nominal mission lasts until December 2010. However, NASA has given the spacecraft enough propellant that, if needed, it could perform its communications relay role for an additional 5 years. With the cancellation of the Mars Telecommunications Orbiter (which was slated to launch in 2009), this extension is likely.

In August 2007, NASA plans to send a new lander to Mars to search for ice under the planet's surface. Named ***Phoenix*** and due to arrive in May 2008, the mission is the first in a series called Mars Scouts — smaller missions aimed at specific sites or data that planetary scientists wish to examine.

The name Phoenix refers to a mythological bird that arose from fire to regenerate itself. It's appropriate: Planners are using many leftover components originally assembled for the cancelled 2001 Mars Lander. The instrument suite includes these carefully stored experiments and also upgraded experiments from the crashed Mars Polar Lander (MPL) of 1999.

2007



2007

2007

▲FOLLOWING A 9-MONTH cruise through space, Phoenix will enter Mars' atmosphere and land at a predetermined site. NASA

◀STATIONARY PHOENIX will use its robotic arm to dig into Mars soil to look for near-surface ice, and then take it aboard for tests. NASA

Like MPL, Phoenix aims for a high-latitude landing site. But unlike MPL, Phoenix will be sent to a site in the northern hemisphere, not the southern. Current planning focuses on a site between 65° and 75° north latitude and around 240° east longitude. Measurements taken from orbit by Mars Odyssey's gamma-ray spectrometer found the ground in the martian arctic contains lots of hydrogen. Calculations indicate that, below a few inches of dry soil, perhaps as much as 80 percent of the ground's volume is water ice — the chosen site shows a water signature nearly as strong as the ice cap itself. Once Phoenix is on the ground, the mission will last 90 sols (martian days, each 40 minutes longer than an Earth day).

In an unusual step, NASA asked outside organizations to compete to manage the Phoenix mission, and awarded the contract to the University of Arizona's Lunar and Planetary Laboratory in Tucson. Peter Smith, who will lead the mission team, plans to construct a simulated landing site and run tests on a full-size replica of the Phoenix lander.

"Our payload has many interactive instruments," he says. "The camera system supports the robotic arm, and the arm will deliver soil and ice samples to the instruments on the lander's deck." But, he adds, "The only way we can test the entire system in a Mars-like, dirty, environment is with our testbed here."

◀PHOENIX WILL ANALYZE the soil chemistry at its landing site to test for components that could be dangerous to astronauts. NASA

▲ THE MARS SCIENCE LABORATORY, with its nuclear power source, will cover more terrain than Spirit and Opportunity. NASA/JPL

Planners expect the testing will uncover issues that can be addressed before the actual launch. "The environment around the spacecraft can be modified to create situations for the science team to grapple with," Smith explains. The group "may find a trench is being created where a rock is — how will we respond?"

Phoenix is a fixed lander that will not roam the surface. But Smith points out its instruments will help others plan the first astronaut visits. The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA), to be built by the Jet Propulsion Laboratory in Pasadena, California, will help reduce the health risk posed to astronauts by Mars' soil.

"Basically, we wish to know for sure the dust isn't poisonous," says Smith, "because there's no way to stop i from getting into the living environment." MECA, he adds, "will characterize the chemistry of the soil and airborne dust."

Phoenix will ferry water from Earth to mix with martian soil samples, then take measurements of the water using special sensors on board. "For Phoenix science, this recreates the situation where the subsurface ice has melted, and will prove whether the plains present a readily available source of ice-generated water" for astronauts' use, Smith predicts. While the lander's mission is not specifically to look for life's past and present traces, the results should help narrow the possibilities.

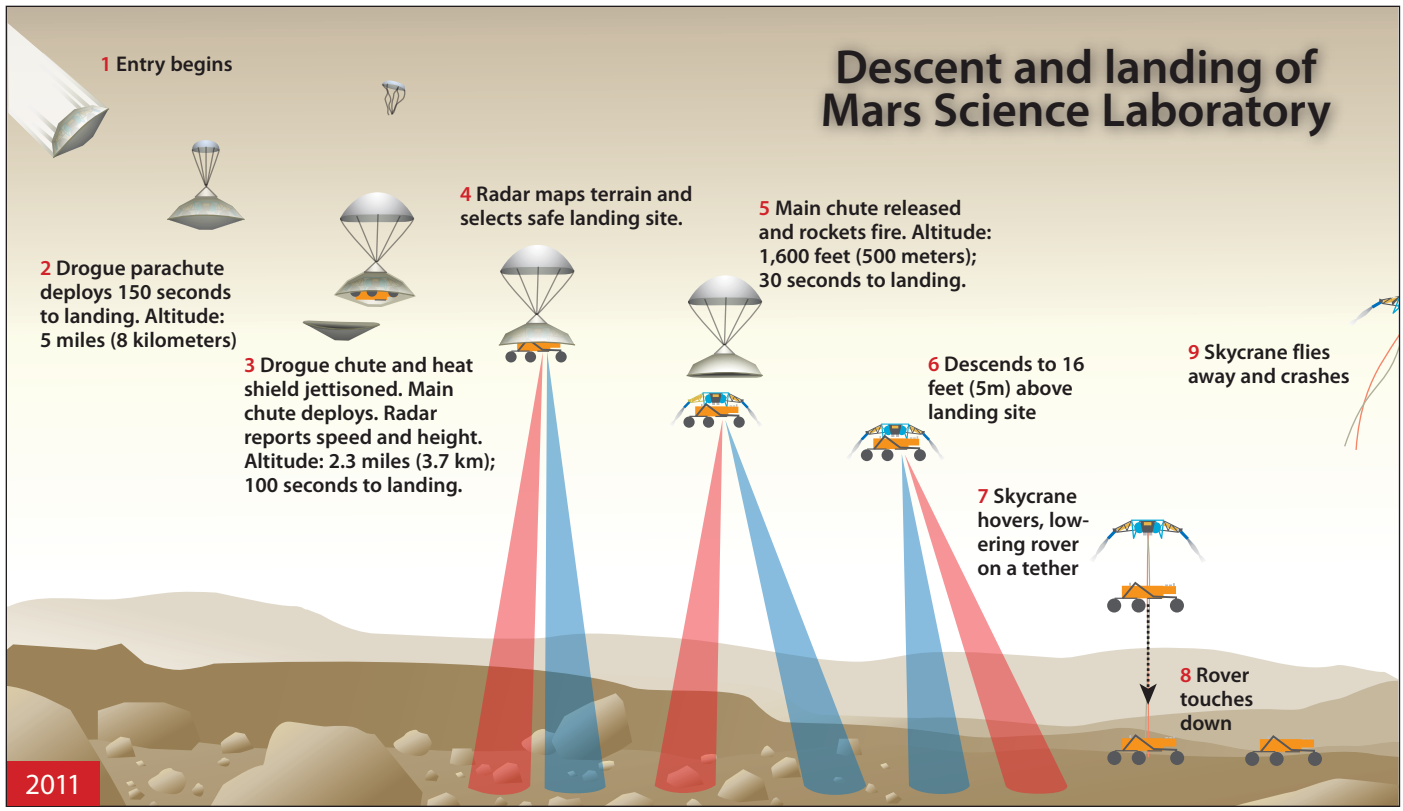
After the first scout mission, NASA's Mars exploration returns to roving — but with a big difference from the two machines currently making their way around the Red Planet.

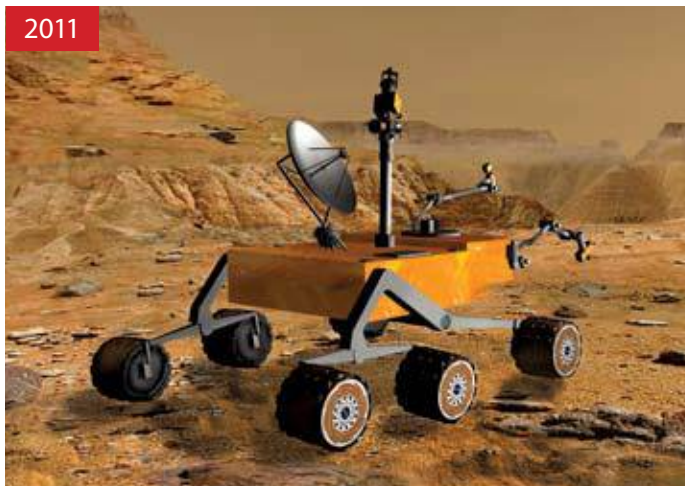
Originally planned for launch in December 2009 with an arrival in October 2010, the ***Mars Science Laboratory (MSL)*** will likely launch in 2011 due to NASA's current budget constraints. This rover is a much larger and more ambitious kind of vehicle than the air now roaming Gusev Crater and Meridiani Planum. If Spirit and Opportunity are each kin to a golf cart, the next Mars rover to be launched will be a Humvee. (In fact, it'll weigh nearly as much as a real Hummer!)

Carrying instruments from several countries as well as from the United States, the lander will consist of a six-wheel roving vehicle able to collect rocks and soil samples. Once onboard, the samples will be analyzed for organic compounds and environmental conditions that could have supported microbial life in the past — or do now. The mast-mounted cameras will help select the most interesting samples for insertion into the rover's onboard test chambers. Once inside, the samples will be subjected to a series of instruments that will analyze their composition for any organic compounds or other acids.

Russia will supply the lab's water-detector; a meteorological package comes from Spain; and one of the three spectrometers is Canadian (with German participation). A focusable micro-imager will function as a geologist's hand-lens, and a laser will be able to zap targets on the ground from up to 30 feet (10m) away to measure the elemental composition of rocks and the soil. A radiation detector prepares for the day when humans will visit. Its purpose is to monitor the broad spectrum of radiation reaching the martian surface, which is essential for scientists to understand before people can visit.

What gives MSL its "legs" is ample power, drawn from a radioisotope power source. This will enable the rover to operate at latitudes up to 60° north or south, where solar energy is weak. A nuclear source also means the spacecraft has plenty of electrical


Descent and landing of Mars Science Laboratory
1 Entry begins
2 Drogue parachute deploys 150 seconds to landing. Altitude: 5 miles (8 kilometers)
3 Drogue chute and heat shield jettisoned. Main chute deploys. Radar reports speed and height. Altitude: 2.3 miles (3.7 km); 100 seconds to landing.
4 Radar maps terrain and selects safe landing site.
5 Main chute released and rockets fire. Altitude: 1,600 feet (500 meters); 30 seconds to landing.
6 Descends to 16 feet (5m) above landing site
7 Skycrane hovers, lowering rover on a tether
8 Rover touches down
9 Skycrane flies away and crashes
2011



▲MSL'S DESCENT AND LANDING will be a highly coordinated maneuver as the skycrane carefully lowers the rover. The payload enters its descent phase 5 miles (8 kilometers) above the surface at Mach 2 (twice the speed of sound). MSL will use sophisticated radar to measure altitude and speed to find a safe landing site. Just 3 minutes after beginning its descent phase, the payload will slow to 2.2 mph, giving the rover a soft landing. *ASTRONOMY:* ROEN KELLY AFTER NASA

◀MSL WILL HAVE 5 times the imaging resolution of Spirit and Opportunity, fitting for a rover that will be much larger. NASA/JPL

power to run instruments more sophisticated and power-hungry than those on Spirit and Opportunity.

The MSL will not land using airbags as both Spirit and Opportunity did. Instead, MSL will fly to a chosen landing site much as the space shuttle glides through the atmosphere toward a landing strip on Earth. Then, drawing near the site, the incoming spacecraft will deploy a parachute and retro-rockets to approach the ground.

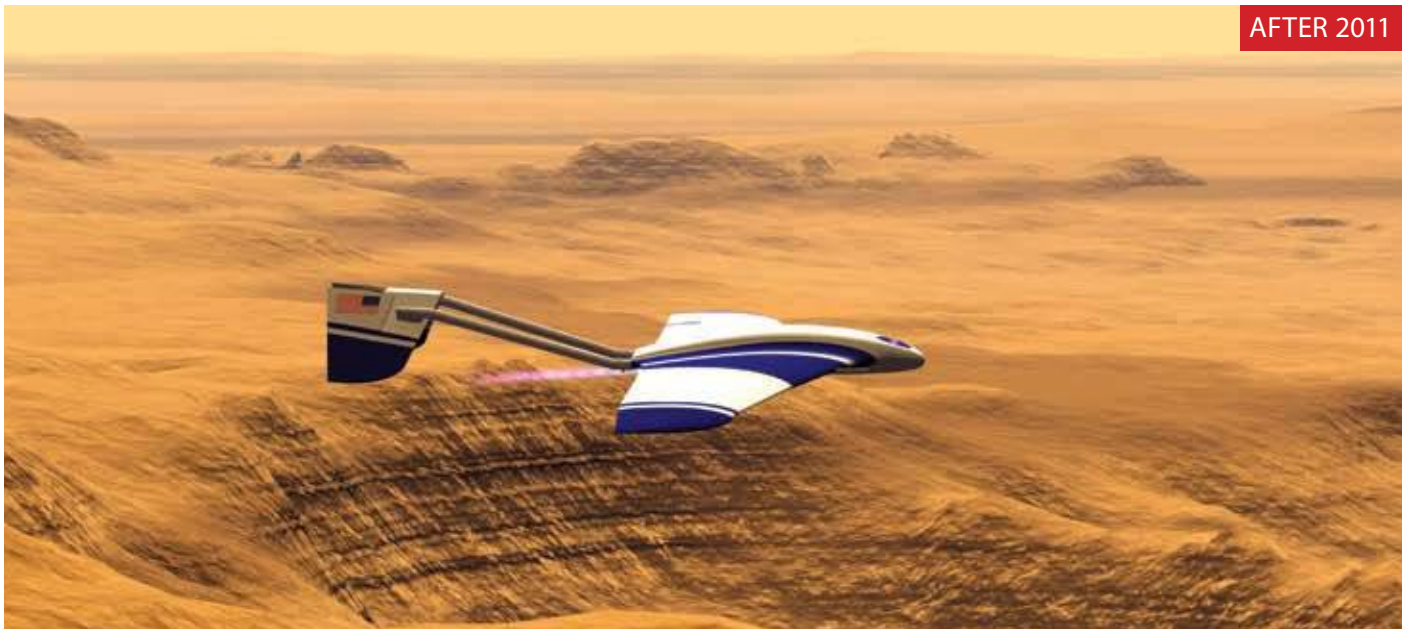
The rocket engine will let the lander hover over the landing site, dangling the rover on a long cable, somewhat like a "skycrane" delivering a heavy object on Earth. When the exact site is found, the hovering lander will set the rover down, release it, and fly away from the immediate locale before making a controlled crash landing where the rover won't be affected.

This landing method acknowledges airbags aren't practical for heavy rovers and landers. It also lets mission planners choose sites that would be tricky to land on if the mission didn't have the precise placement that the hover-and-dangle skycrane system permits. Scientists expect images from the MRO will be important for MSL's final site selection.

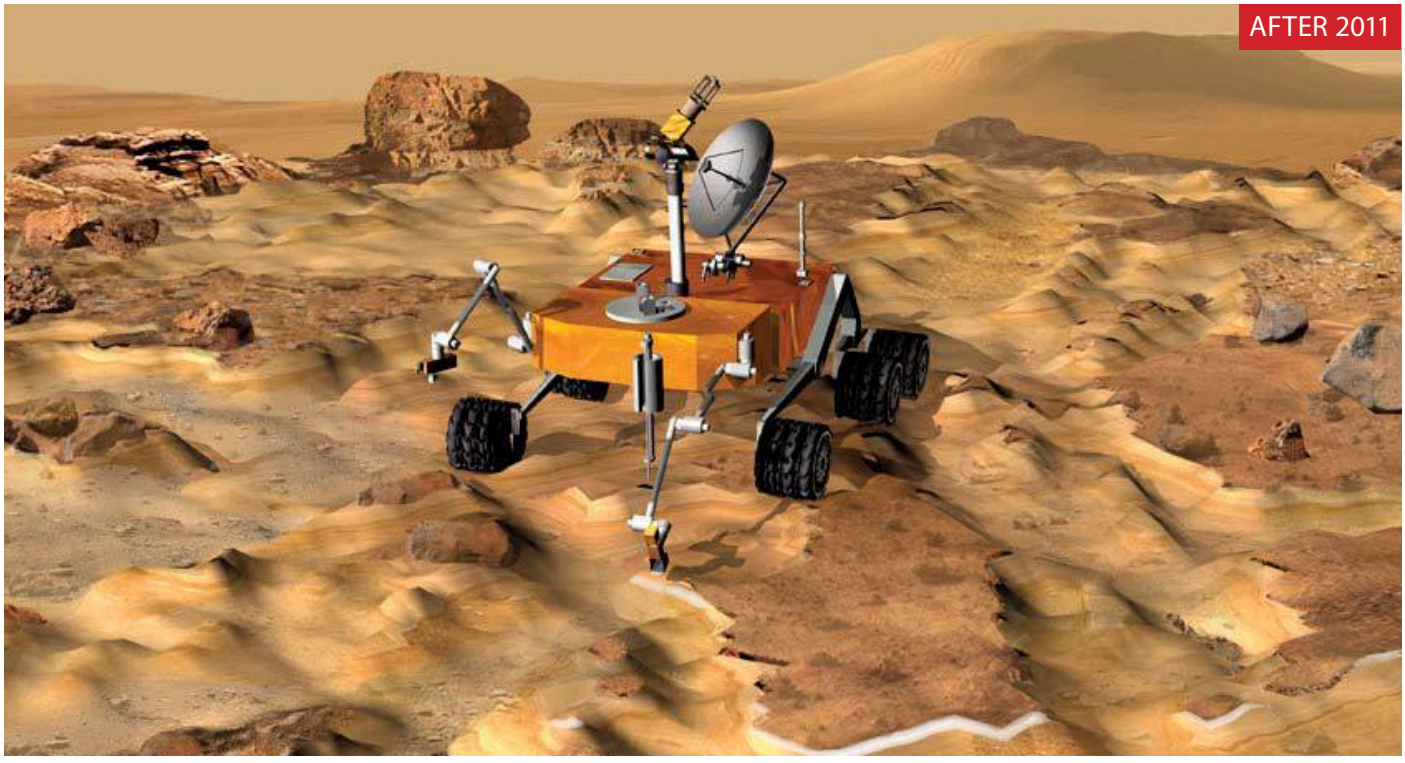
NASA's baseline mission for the MSL is one martian year (670 sols, or 687 Earth days). With the launch possibly pushed back to 2011, NASA will have extra planning time. In this situation, NASA might adopt the same insurance policy it used with Spirit and Opportunity — build two at the same time and fly both.

NASA has longer-range missions under study, although they're not mature enough for a formal proposal nor are they on the agency's schedule or budget horizon.

After the Mars Science Laboratory, a ***second Scout mission*** would follow. This advanced Scout might carry payloads such as balloons or aircraft that could be deployed for long-duration



ARES, A LOW-FLYING Scout glider, would explore (if chosen by NASA) the Red Planet's lower atmosphere, an area not yet researched, giving scientists low-level views of the planet. NASA

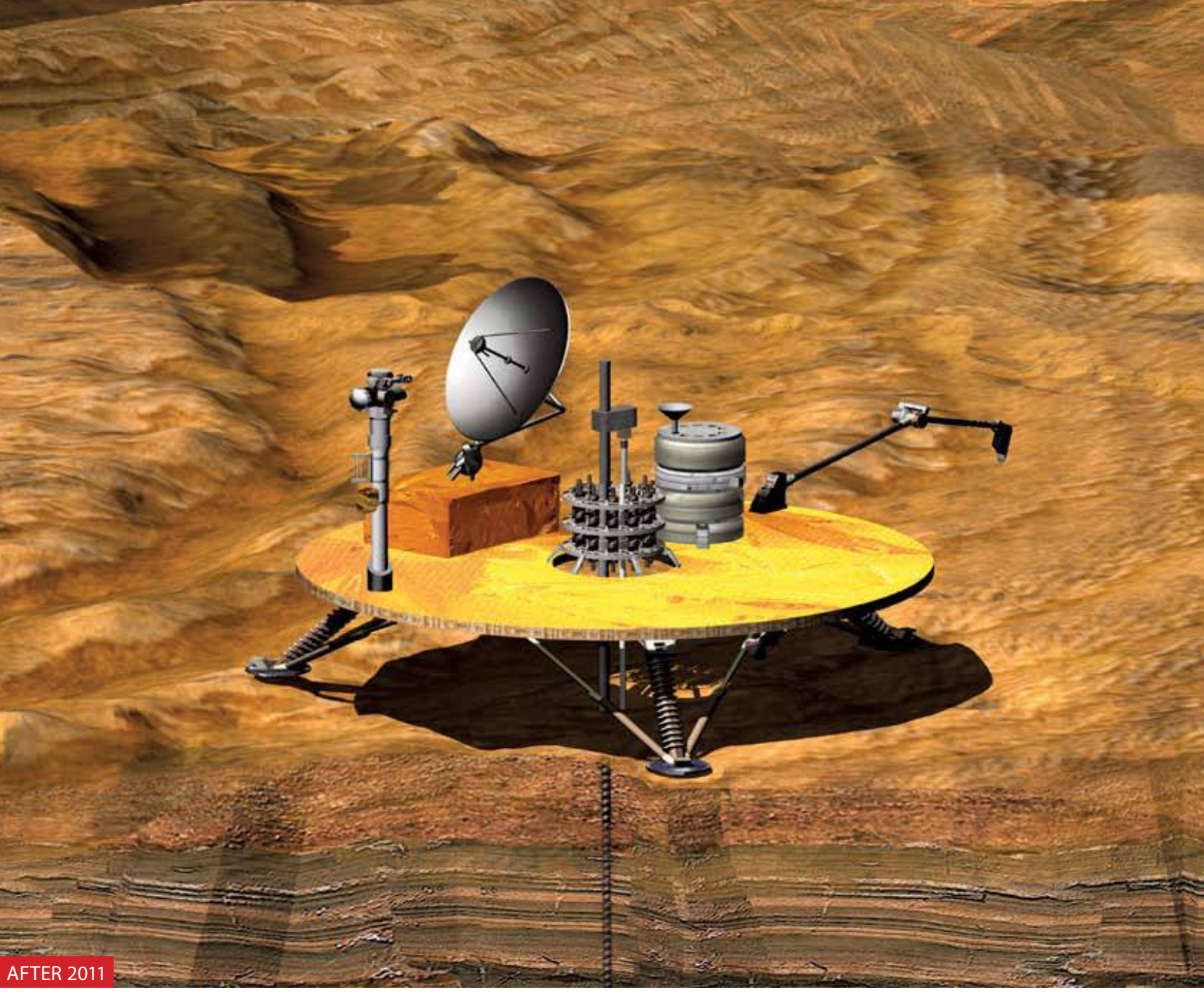


A PROPOSED Astrobiology Field Laboratory will search for signs of past — or present — life at sites determined by the MSL. NASA/JPL

surveillance flights in the upper martian atmosphere. The earliest NASA might conduct a second Scout mission is 2011.

Two such ideas considered are ***SCIM*** (Sample Collection for Investigation of Mars), a high-dive through the planet's upper atmosphere, and ***ARES*** (Aerial Regional-Scale Environmental Survey), a low-flying aircraft to explore the near-surface atmosphere. Each project would explore a regi?n lower than orbiting missions but above the planet's surface.

Then there is the most daring, and complicated, robotic mission of all, the flight that brings back to Earth a sample of Mars. Such a venture has been under study for decades. A ***sample-return mission*** would require a host of advanced technologies not yet



AFTER 2011

mature, from autonomous rendezvous and docking to precision surface-launch capabilities.

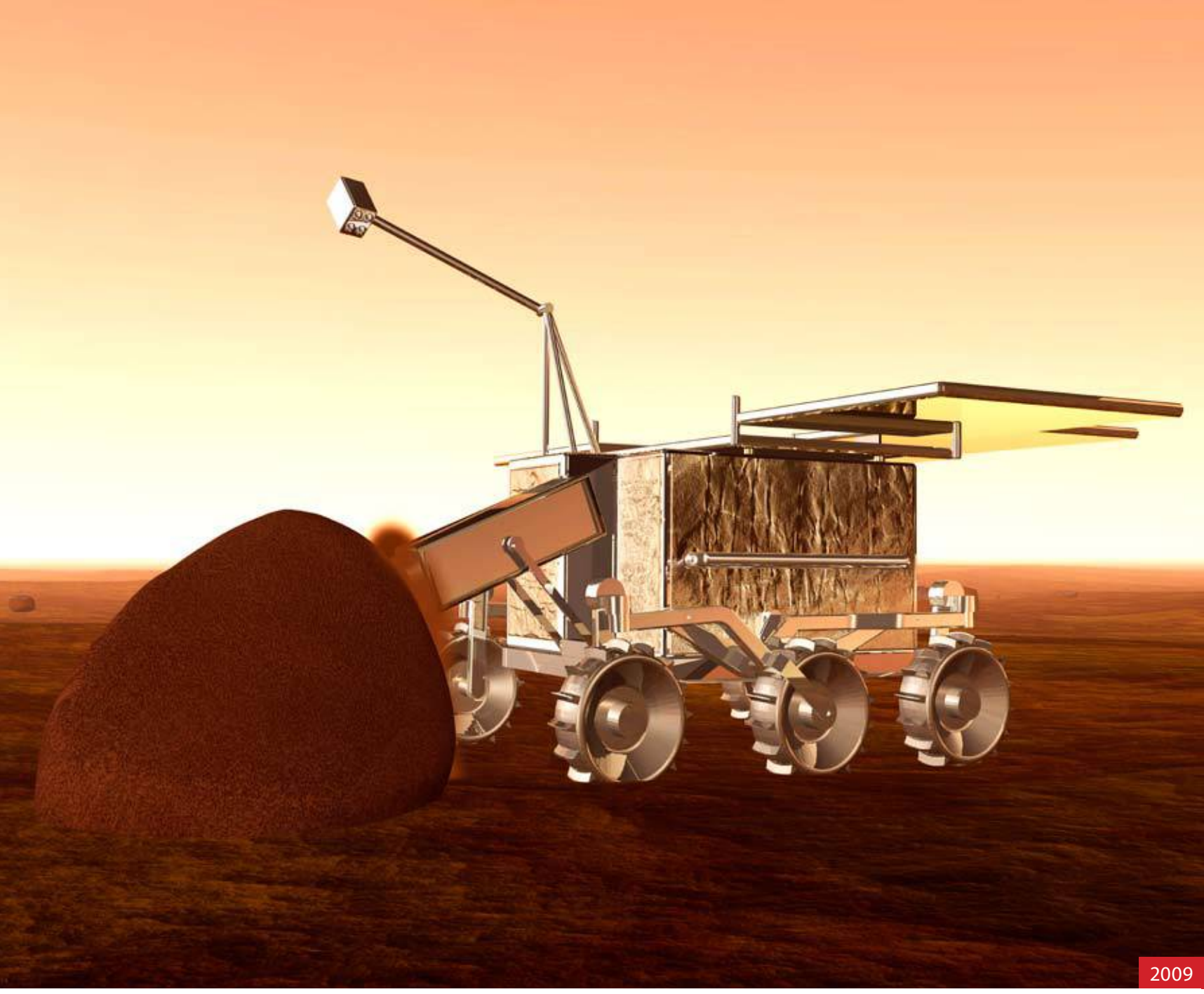
As envisioned by mission planners, a booster rocket would launch the sealed Mars soil sample into orbit. There, it would rendezvous with a vehicle for transport to Earth.

While on the surface, the sample-return rover would need highly developed instrumentation and artificial intelligence systems that could distinguish targeted sites, change them as needed, prepare candidate samples, and make a detailed preliminary analysis to choose samples for the return flight.

By adding tests and features to precursor missions, NASA can develop technology for precision landings, and ascent, rendezvous, and docking in Mars orbit. Equally tricky will be sealing the Mars surface samples into a reentry vehicle for the return trip — and making sure the vehicle stays sealed throughout the Earth reentry and recovery. No one wants a repeat of the Genesis capsule landing, in which a sealed sample of solar-wind particles broke open when the capsule crashed in the Utah desert September 8, 2004.

▲ **A DEEP-DRILLING SYSTEM, although not yet on NASA's Mars schedule, could find ice beneath the Red Planet's surface.** NASA/JPL

Beyond the challenge of the sample return, NASA is considering other landers and rovers, such as an ***Astrobiology Field Laboratory*** to continue the search for life, and other landing craft that could carry miniaturized ***deep-drilling systems***. While these surface missions are underway, new orbiters and communications-



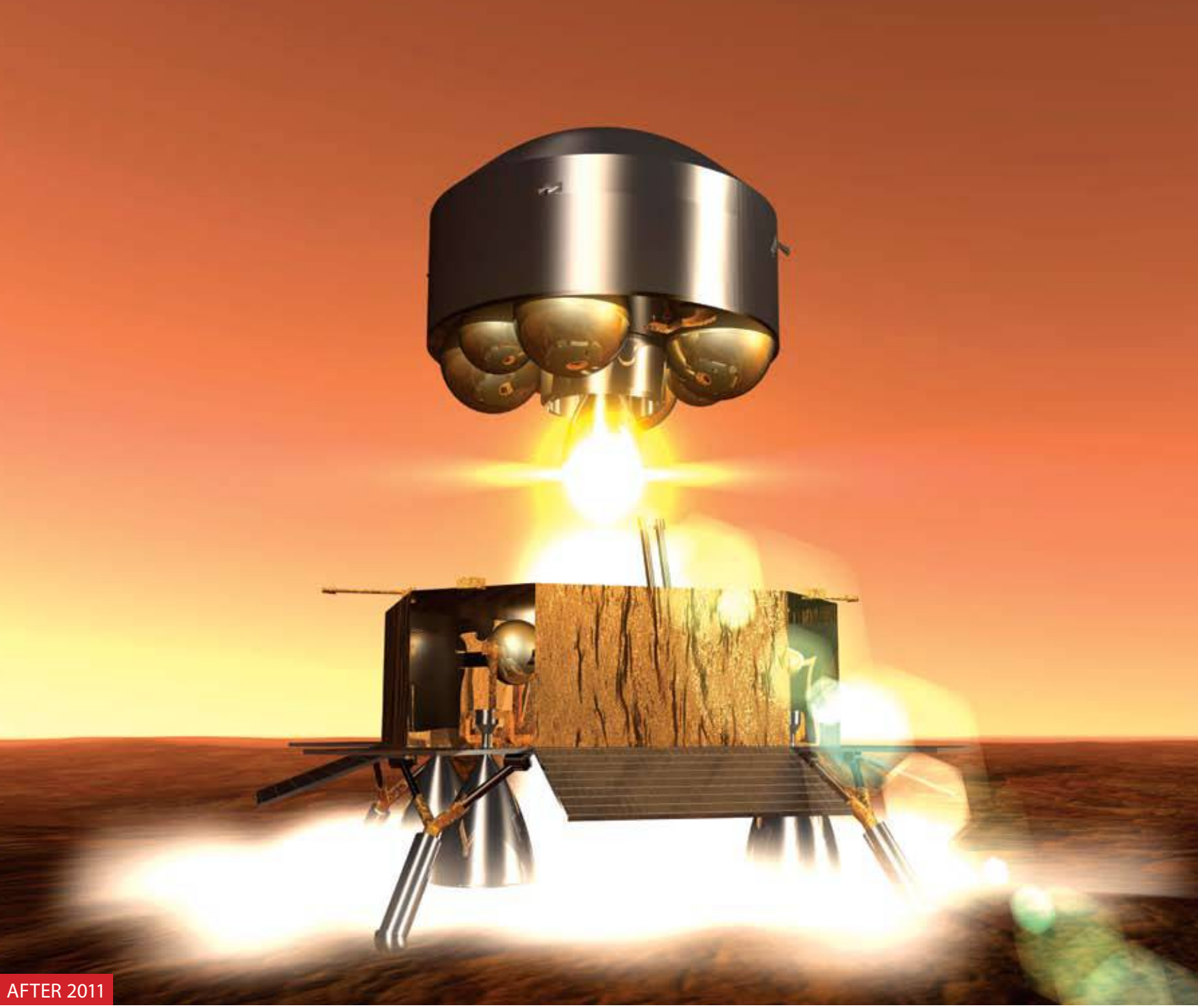
relay spacecraft may be placed in martian orbit to prepare the way for the first manned missions.

The European Space Agency (ESA) has designed a solar-system exploration program named Aurora that will combine both robotic and human missions to the Moon, Mars, and asteroids. The program features both large so-called flagship missions and smaller "arrow" missions. While the for r addrlss ambit s tasks and operations (and have correspondingly larger budgets), the latter (with smaller budgets) help develop technologies to support the major missions. The overall Aurora program, however, is less extensive than NASA's, in part because ESA has to work within 16 member-nations' budgets and priorities.

▲ **ESA'S EXOMARS ROVER will be able to drill through rocks and move large roadblocks to test Mars' chemistry and biology.** ESA

But Aurora has already begun. ***Mars Express***, currently in orbit, is ESA's first mission to the Red Planet. Others are in the works, including an ***arrow-class mission*** scheduled for 2007 to develop new Mars-entry technologies, perhaps involving an inflatable aeroshell/heat shield.

The first flagship-class mission is ***ExoMars***, which has a 2009 target launch date. The mission unites an orbiter, descent module, and rover into a single spacecraft capable of navigating to Mars and getting itself into orbit. Once in orbit, the descent module (plus rover) separates from the orbiter and heads for the surface.



AFTER 2011

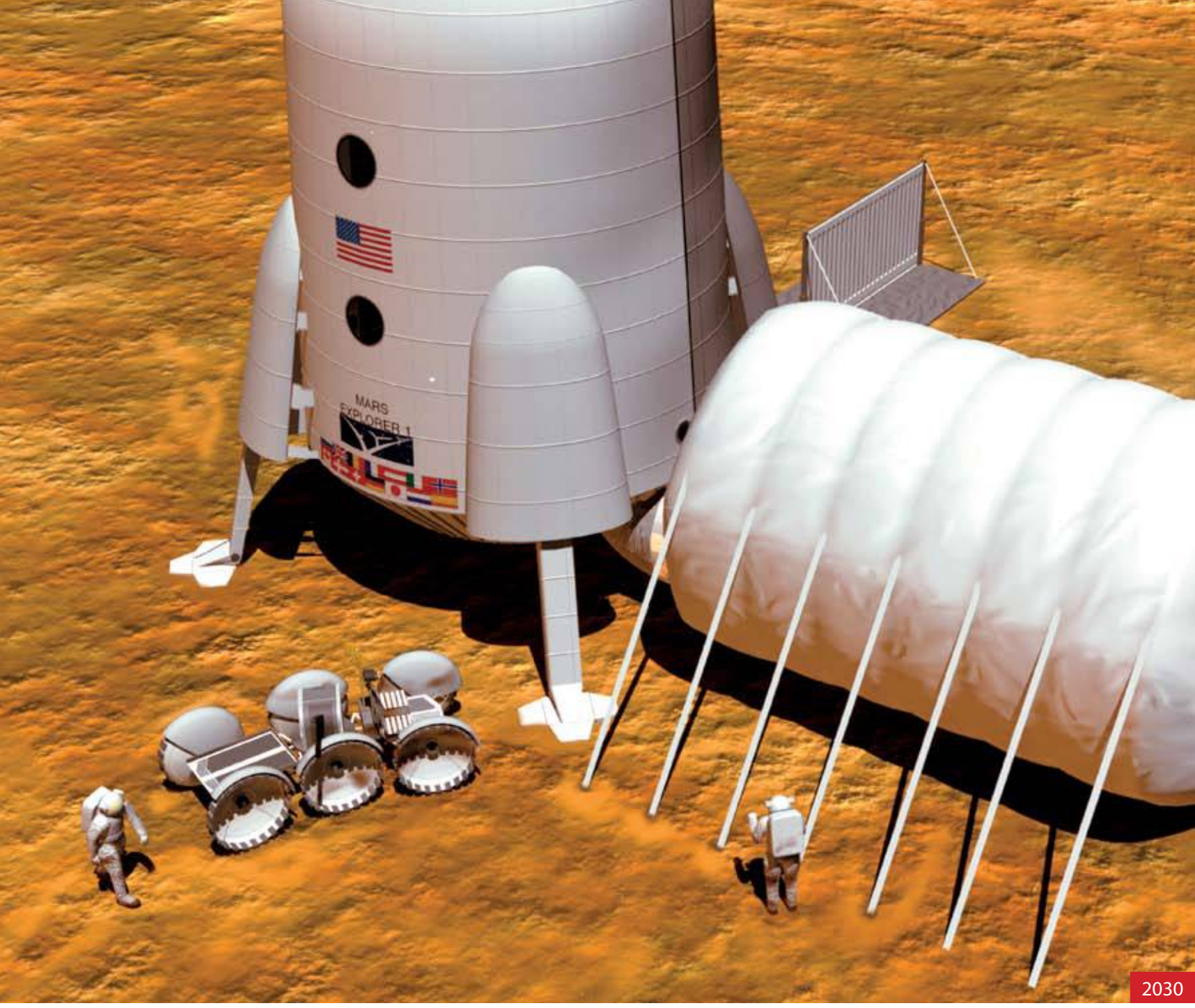
The rover, solar-powered like Spirit and Opportunity, is about their size and, like them, gets around on six wheels. Plans call for it to drive itself at least a few miles on the surface. Where ESA's rover surpasses the two NASA rovers is in the instrumentation. ExoMars has a payload of approximately 85 pounds (Earth weight) focused on exobiology. Its equipment includes a lightweight drilling system, a sampling and handling device, and a set of scientific instruments to search for signs of past or present life.

The orbiter, meanwhile, transfers itself into a more suitable orbit from where it will operate as a data-relay satellite. Initially, it will relay data for the ExoMars rover, but its life may be extended to serve future missions.

▲ **ESA'S SAMPLE-RETURN mission will explore the surface, and then carry soil samples back tk)the orbiter via an ascent module.** ESA

Following ExoMars is ***ESA's sample-return mission***. This ambitious mission calls for five spacecraft, each designed for a specific stage of the mission: an Earth-Mars transfer vehicle, a Mars orbiter, a descent module, an ascent module, and an Earth reentry vehicle. The Mars orbiter and Earth reentry vehicles could be launched as early as 2011, with the rest following in 2013.

The flight plan dictates that once samples of martian soil have been collected — their total weight will be about a pound (Earth weight) — they will be loaded into the Mars ascent vehicle. This



will be launched into martian orbit to rendezvous with the Earth reentry vehicle. After rendezvous, the Earth reentry vehicle returns to Earth on a ballistic trajectory with the soil and atmospheric samples. After recovery, the samples will be isolated in a laboratory to prevent contaminating them and allow scientists to analyze them safely.

NASA plans to return astronauts to the Moon by 2020. With ***Project Constellation***, the space agency is studying the first series of missions to pick up human exploration of the Moon where the Apollo astronauts left off, in the early 1970s. The missions, now under detailed study and in early planning, will again target the Moon's equatorial regions, first the smoother maria and then more challenging targets.

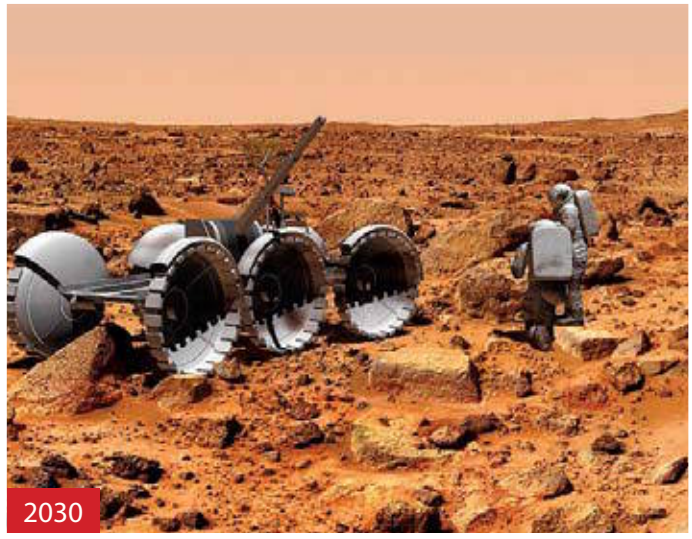
▲ ASTRONAUTS WILL NEED a base to call home. Maybe the inside will be green and blue, as a change from Mars red. NASA/JOHN FRASSANITO & ASSOCIATES

Another wave of landings will tackle the lunar poles, and would eventually lead to construction of permanent lunar bases there. Under the Moon-to-Mars initiative, these bases would have some of the types of facilities, equipment, and power systems that the first Mars outposts will need.

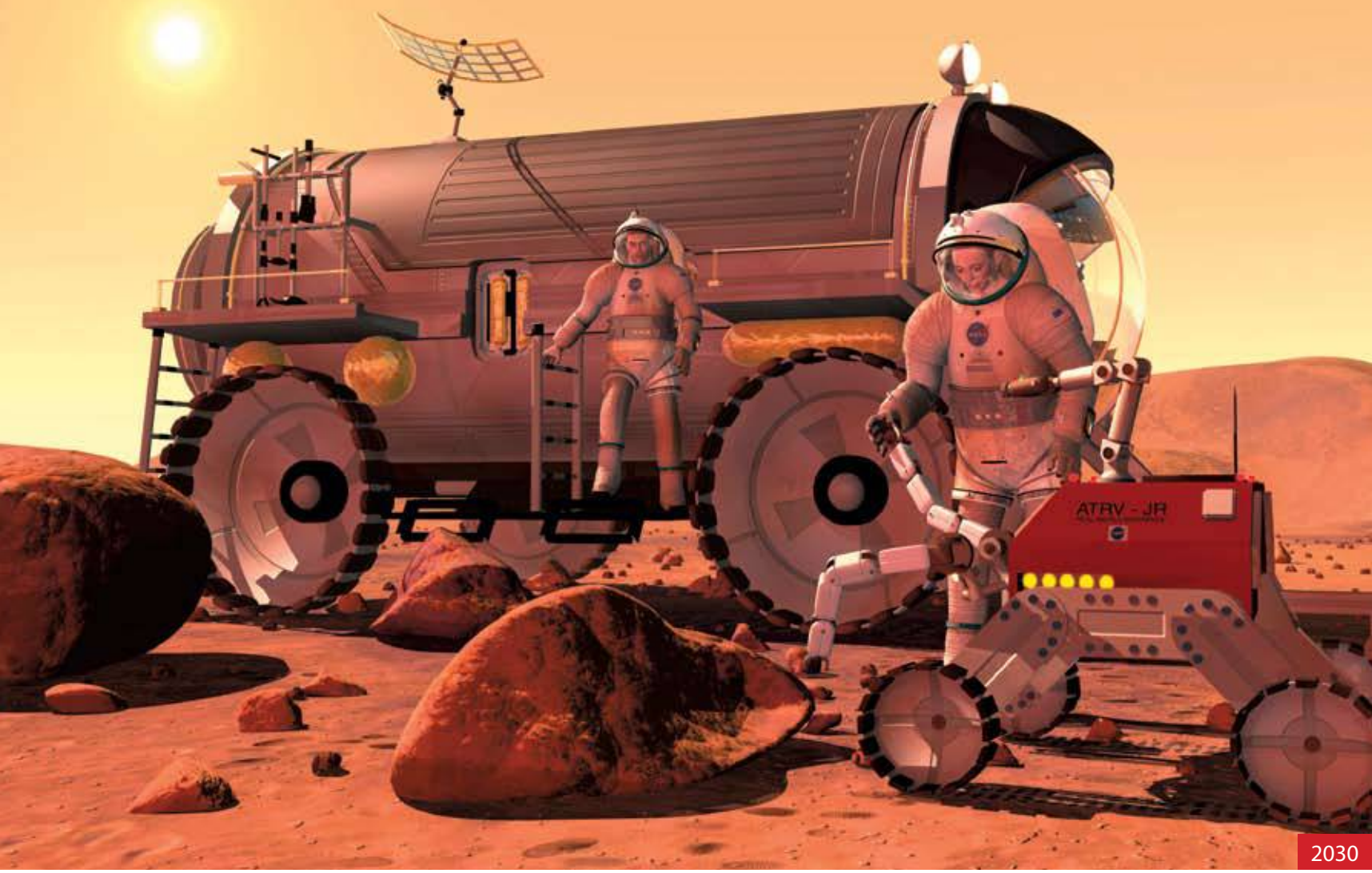
Under the exploration-planning directive developed from Moon-to-Mars goals, the Moon in the next decade becomes a

▲ **THE SEARCH FOR LIFE** on Mars likely will require an array of experiments, and humans to operate them. Manned missions have a key advantage over robotic missions: Humans may better recognize signs of life. NASA/JOHN FRASSANITO & ASSOCIATES

▲ **A POSSIBLE MARS BASE** includes a habitat, fuel station, research equipment, and a return-to-Earth vehicle. NASA/JOHN FRASSANITO & ASSOCIATES



▲ **AFTER DRIVING AROUND** the surface to find a test area, astronauts collect Mars soil data. NASA/JOHN FRASSANITO & ASSOCIATES



HUMAN EXPLORATION of Mars will be just one step in our exploration of the solar system. After repeated visits to the Red Planet, humans may venture to Saturn's Titan or Jupiter's Europa — two moons possibly harboring past or present life. NASA/JOHN FRASSANITO & ASSOCIATES

testing and training ground for the Mars flights to follow, projected for the 2030s. (The manned part of ESA's Aurora program envisions a similar approach, using the Moon as a steppingstone to Mars.)

According to Craig E. Steidle, former head of NASA's Exploration Systems Directorate, the first human m sions to Mars will use an advanced version of the Project Constellation ***Crew Exploration Vehicle (CEV)*** and may carry six crew members. Steidle says the first human visits to Mars will fly circumnavigation missions into Mars orbit.

The first flights to the Red Planet will be extended-duration visits. Astronauts will study preselected landing sites from orbit using advanced cameras and sensors. Later Mars orbital flights might see astronau s sending cargo or power packages down to the surface in preparation for building the first robotic/human base camps.

Planners are following the logic of the building-block approach that was used in designing past lunar missions: build up stay times and land more sophisticated equipment packages as the base camps are expanded. But even before they journey to Mars, astronauts may get other testing missions to prepare them for the complex journey. NASA planning documents suggest possible flights of the Mars-capable CEV to a near-Earth asteroid or sending a crew to construct or upgrade a future deep-space telescope.

First, though, the robotics program must pave the way. "Exploration Systems is working closely with the Science Mission Directorate to define robotic precursor missions, to provide reconnaissance of potential landing sites, and demonstrate advanced technologies for future human missions," Steidle says. "The Science Directorate's work is vital to the Vision for Space Exploration to place humans on the surface of Mars," he adds.

Thus, in the next decade, NASA and the ESA, individually or jointly, will attempt a truly sustained program of robotic missions to Mars. At the same time, astronauts — as well as their robotic companions — will develop their skills and gain experience on the Moon that's needed for future visits to Mars.

Starting with Spirit and Opportunity in early 2004, the advanced scientific assault on the Red Planet has only just begun.

Frank Sietzen, Jr., *is a space journalist based in the Washington area, and the coauthor of* New Moon Rising: The Making of America's New Space Vision and the Remaking of NASA *(Apogee Books, 2004).*

Valles Marineris — the Grand Canyon of Mars — stretches 2,500 miles and dips 4.5 miles beneath the surrounding plain. This 40-mile-wide swath of the canyon shows details as small as 40 feet across. ESA/DLR/FU BERLIN (G. NEUKUM)